Appendix A

Trip A-6

LATE OTTAWAN DUCTILE SHEARING AND GRANITOID EMPLACEMENT IN THE HUDSON HIGHLANDS, NY

Matthew L. Gorring, Department of Earth & Env. Studies, Montclair State University, Upper Montclair, NJ 07043
David W. Valentino, Department of Earth Sciences, SUNY-Oswego, Oswego, NY 13126
Gary S. Solar, Department of Earth Sciences, SUNY College at Buffalo, Buffalo, NY 14222
Alexander E. Gates, Department of Geology, Rutgers University, Newark, NJ 07102

INTRODUCTION

The purpose of this field trip will be to examine rocks exposed in the Hudson Highlands, NY that elucidate the late Ottawan (<1030 Ma) history of high-grade ductile shearing, migmatization, and the emplacement of a variety of granitoid plutons. Most research in the Grenville Province in eastern North America has focused on the history and processes associated with Elzeverian (1350-1180 Ma) and Ottawan (1090-1030 Ma) orogenic events and intervening periods of extension and magmatism (see McLelland et al., 1996; Rivers, 1997; Hamner, 2000 for review). In contrast, comparatively little attention has been given to late- to post-Ottawan events and their importance to the history of the Grenville Province. The period between 1030 and 960 Ma is generally characterized by a diverse set of events that include both large-scale orogenic collapse along major extensional shear zones (e.g., van der Pluijm and Carlson, 1989; Carlson et al., 1990; Culshaw et al., 1994; Ketchum et al., 1998; Streepey et al., 2000) and localized high-grade metamorphism, thrusting, and magmatism (e.g., Lumbers et al., 1990; Mezger et al., 1991; Ratcliffe et al., 1991; Gower et al., 1991; Connelly and Heaman, 1993; Owens et al., 1994; Haggart et al., 1993; Jamieson et al., 1995; Corfu and Easton, 1997). Recent geologic mapping and structural analysis in the central Adirondack Highlands and the New Jersey/Hudson Highlands has also recognized the importance of late- to post-Ottawan, high-grade, ductile transpression (Gates, 1998; Allers et al., 2001; Valentino et al., 2001; Solar et al., 2003; Gates et al., 2001a; in press). This deformation is being taken up on large transcurrent shear zones with significant amounts of displacement (Gates, 1995; 1998). In the New Jersey/Hudson Highlands, the emplacement of a chemically diverse suite of granitoid plutons is intimately associated with this crustal-scale shearing event (Gorring et al., 2002). A Middle Proterozoic escape tectonic event (e.g., Tapponnier et al., 1982) in the central Appalachians resulting from accretion to the north is interpreted to have produced this deformation and magmatism.

REGIONAL GEOLOGY

The Hudson Highlands, along with the physically contiguous New Jersey Highlands and similar rocks extending into eastern Pennsylvania, are collectively called the Reading Prong, one of the largest of several Grenville-age (1300 to 1000 Ma) basement massifs within the core of the Appalachian orogenic belt of eastern North America (Figs. 1 and 2; Rankin, 1975). These basement massifs lie outboard (east) of the main Grenville Province in eastern Canada and record variable amounts of post-Mesoproterozoic metamorphic and deformational overprint (e.g., Rankin et al., 1989; Gates and Costa, 1998). The Reading Prong displays evidence of only brittle deformation concentrated along narrow, reactivated Mesoproterozoic shear zones due to late Paleozoic compression and Mesozoic rifting (Gates, 1995; 1998) and thus, have a well preserved record of Grenville-age metamorphism and deformation. Rocks of the Hudson Highlands consist of a complex assemblage of metasedimentary, metavolcanic, and quartzofeldspathic ("granitic") gneiss, and intrusive granitoid rocks that were variably deformed and metamorphosed at upper amphibolite to hornblende-granulite facies conditions during at Grenville orogenesis (Dallmeyer and Dodd, 1971; Dallmeyer, 1974; Helenek and Mose, 1984). Based on field relations and a limited amount of recent U-Pb zircon ages (Helenek and Mose, 1984; Aleinikoff and Grauch, 1990; Ratcliffe, 1992; Ratcliffe and Aleinikoff, 2001; Gates et al. 2001a), the rocks of the Hudson Highlands can be roughly divided into two groups: (1) pre-Ottawan (>1090-1030 Ma) and (2) late- to post-Ottawan (<1030 Ma). Pre-Ottawan rocks all have strong, penetrative, high-grade metamorphic fabrics related to the Elzeverian and/or the Ottawan orogeny.

Late- to post-Ottawan rocks are variably deformed, ranging from undeformed to those that locally have strong, high-grade, ductile fabrics but lack the regional-scale, penetrative fabrics that characterize the pre-Ottawan rocks. Locally, late- to post-Ottawan rocks truncate fabric elements in pre-Ottawan rocks.

The area of the field trip is located in parts of the Sloatsburg, Thiells, Monroe, Popolopen Lake, and West Point quadrangles west of the Hudson River within the west central Hudson Highlands, New York (Figs. 2 and 3). Previous mapping in this area, divided the units by rock types (Dodd, 1965; Jaffe and Jaffe, 1973; Dallmeyer, 1974; Helenek and Mose, 1984). Considering that about 80% of the rocks are quartz-feldspar gneisses, this system is useful for geologic maps but not for purposes of tectonic reconstructions. Gundersen (1986) suggested that lithologic and stratigraphic associations and sequences should be grouped as units. This system of mapping rock types is adopted for this field guide (Fig. 3).

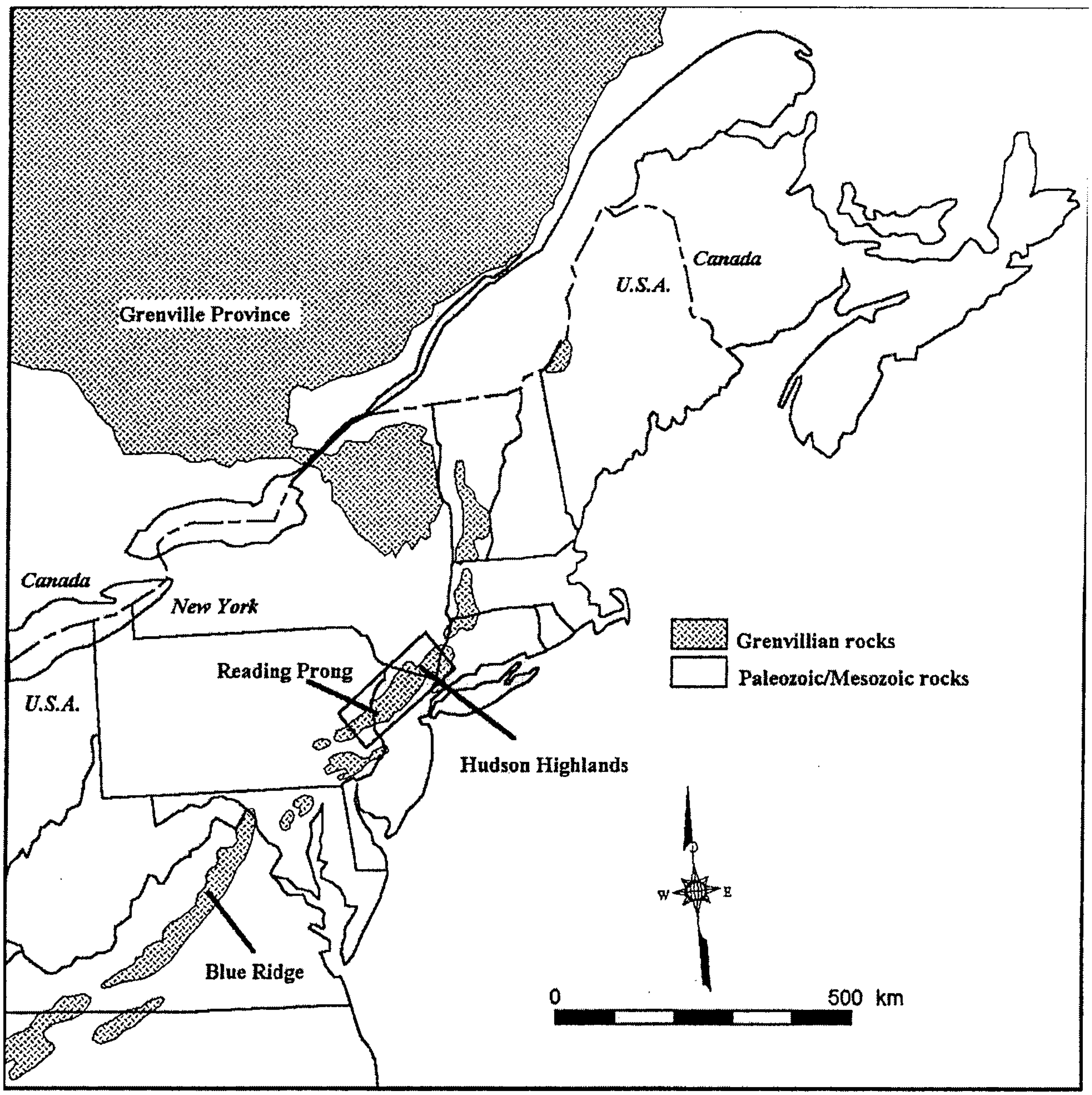

Figure 1. Regional map of eastern North America showing the geographic distribution of Grenville rocks. The area of Figure 2 is outlined by a rectangle. Map from Gates et al. (2001c).

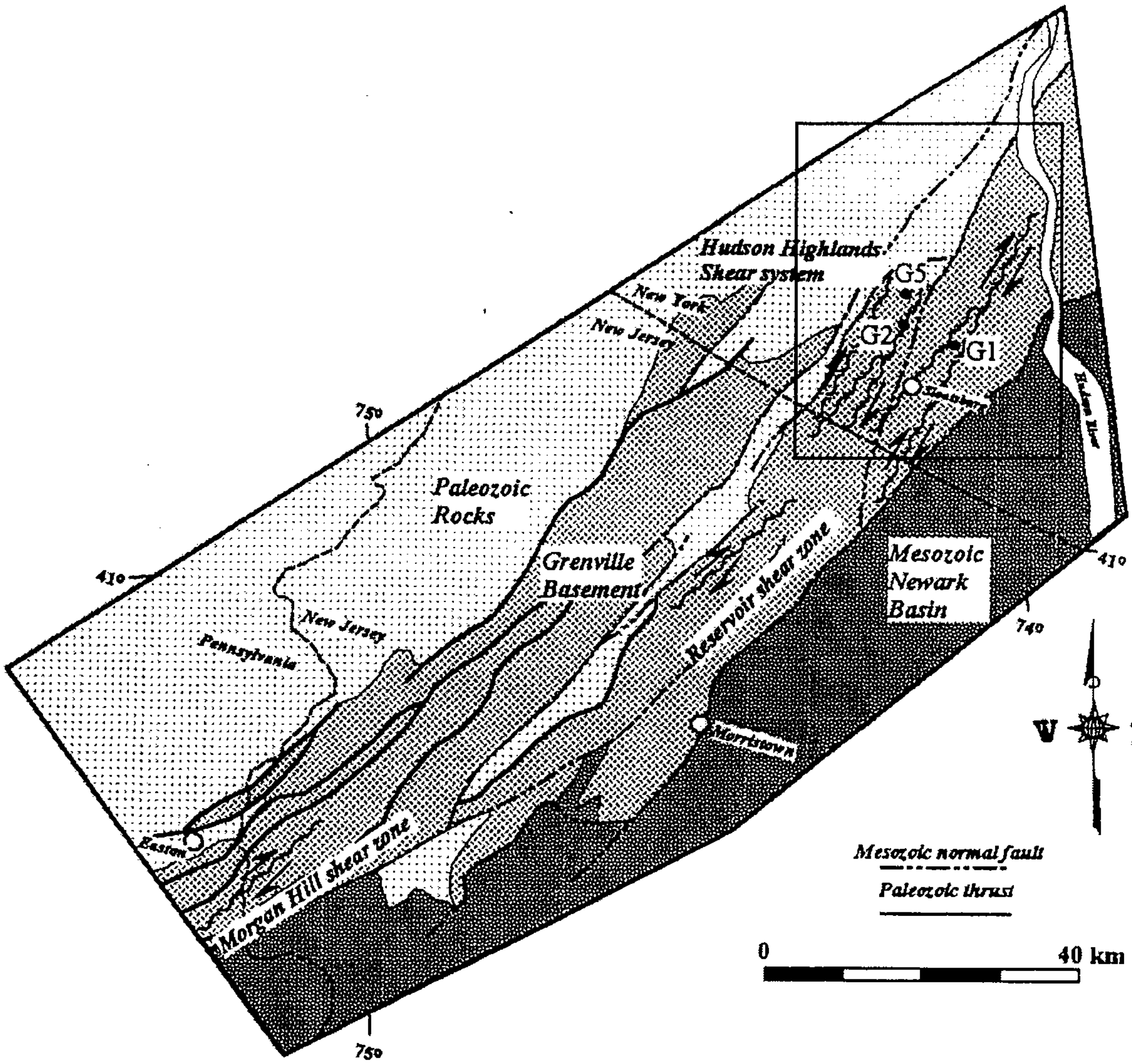

Figure 2. General geologic map of the Reading Prong and Hudson Highlands. The study area shown in Figure 3 is outlined by a box. G1, G2, and G5 are sample localities where Gates et al. (2001b) obtained SHRIMP U-Pb zircon ages. G1 is the Lake Tiorati Metadiorite at Stop #4 (see Fig. 6) and G2 is the sheared quartzofelsdpathic gneiss at Stop #3 (see Fig. 4). Map modified from Gates et al. (2001c).

PRE-OTTAWAN ROCKS

Metavolcanic Lithofacies

Perhaps the oldest rocks in the region are a suite of quartzofeldspathic orthogneiss which include strongly banded, intelayered, very light colored, biotite- and/or hornblende-quartz-plagioclase gneiss, charnockitic (orthopyroxene-bearing) quartz-plagioclase gniess, and amphibolites of mafic to intermediate compositions. Mafic, intermediate, and felsic compositional banding ranges in thickness from 5 cm to 5 m with varying proportions of each rock type. There are local interlayers of quartzite and calc-silicate gneiss. Migmatites also occur locally in this unit. These rocks are interpreted to represent a continental volcanic-plutonic arc suite of calc-alkaline rocks mixed with minor sediments (Ratcliffe, 1992; Gates et al., 2001c). Rocks equivalent to the metavolcanic lithofacies extends southwestward into the New Jersey Highlands where it is called the Losee Metamorphic Suite (Volkert and Drake, 1999) and northeastward into the eastern Hudson Highlands (Ratcliffe, 1992). Rocks of the metavolcanic lithofacies are lithologically and chemically very similar to tonalitic and charnockitic gneisses found in the southern Adirondacks (McLelland and Chiarenzelli, 1990) and to the Mount Holly Complex in the Green Mountain Massif in Vermont (Ratcliffe et al., 1991), which have been dated at ~1350 to 1300 Ma.

Metasedimentary Lithofacies

Throughout the western Hudson Higlands there are belts of rock considered to have sedimentary protoliths including pelitic-, psammitic-, calcsilicate-gneisses, quartzite, and marble. Belts of rock upward of a few kilometers wide may contain all or some of these rock types, interlayered at the scale of meters to 100's of meters. These rocks have been included in the metasedimentary lithofacies that is portrayed on the geologic map (Fig. 3). The metapelite consists of interlayered biotite-garnet gneiss with medium to coarse quartz, plagioclase, K-feldspar and local sillimanite, and cordierite with quartzofeldspathic layers. Within the metapelite are zones of graphite-pyrite-garnet gneiss with biotite, quartz, K-feldspar, plagioclase, and sillimanite locally. Quartzite layers of 10-50 cm thickness also occur within this unit as do rare and discontinuous layers of diopside and diopside-garnet marble to calcsilicate of 10 cm to 2 m thickness. The calc-silicate is quartzofeldspathic with salite, apatite, sphene, scapolite, and hornblende, and is commonly migmatitic. Metaturbidite rocks are interlayered metapelite and metapsammite at the cm-scale, and are ubiquitously migmatites of metatexite (stromatic) and diatexite (structurally disrupted) types with variable degrees of disruption of the rock structure. These rocks are typically residual in mineral content suggesting melt loss.

Based on the abundance of graphite-sulfide rocks and the presence of minor interlayers of amphibolite of probably volcanic origin, Gates et al. (2001b) interprets this sequence as most likely a suite of continental- to oceanic-arc extensional basin deposits. Volkert and Drake (1999) came to a similar conclusion based on field relations and whole-rock geochemical data on correlative rocks in New Jersey Highlands. Similar packages of metasedimentary rocks are common in the Adirondacks (e.g., McLelland et al., 1996) and in the Central Metasedimentary Belt in Canadian Grenville (e.g., Rivers, 1997, Carr et al., 2000).

The contacts with the quartzofeldspathic gneiss (see below) and rocks of the metavolcanic lithofacies are usually gradational such that age relations based on field relations are ambiguous due to transposition of original stratigraphic and/or cross-cutting relations. However, in the New Jersey Highlands, Volkert and Drake (1999) have recognized field evidence that indicates that the correlative metasedimentary sequence unconformably overlies the equivalent of the metavolcanic lithofacies (Losee Metamorphic Suite). Demonstrably unconformable relations between these units in the Hudson Highlands has yet to be recognized in the study area of this field trip, however, Ratcliffe (1992) also places the equivalent of the metavolcanic lithofacies in the eastern Hudson Highlands at the base of the "stratigraphy", below metasedimentary rocks. Dodd (1965) and Helenek and Mose (1984) document a few localities where metasedimentary lithofacies rocks are crosscut by metaplutonic quartzofeldspathic gneisses (e.g. Storm King granite gneiss) in the Popolopen Lake quadrangle near Bear Mountain. Thus, the age of the metasedimentary lithofacies rocks is roughly constrained to be possibly younger (or at least contemporaneous) than the metavolcanic lithofacies (<1300-1350 Ma), but clearly older than quartzofeldapthic gneiss unit (see below) which has recently been dated at ~1175 Ma by SHRIMP U-Pb zircon techniques (Ratcliffe and Aleinikoff, 2001).

Quartzofeldspathic Gneiss

The quartzofeldspathic gneiss ranges from massive to layered quartz-plagioclase gneiss and quartz-K-feldspar-plagioclase gneiss with minor amounts of clinopyroxene, hypersthene, hornblende and/or biotite. Locally, this unit contains magnetite or garnet in trace amounts. Compositional layers are defined by the proportion and type of the ferromagnesian mineral component. Locally, this unit contains apparent textural gradation across the fabrics by an increase in the amount of mica and decrease in layer spacing with sharp contacts between, suggesting a relict sequence. However, such relict sequences in granulite terranes are difficult to interpret. Quartzofeldspathic gneiss is locally interlayered with quartzite and with mafic gneiss at the contact with the metavolcanic lithofacies. The gradational contacts with the metavocanic and metasedimentary lithofacies, and the internal compositional layers suggest that parts of the quartzofeldspathic units could represent a volcaniclastic sequence.

However, in the more massive rocks, this unit is strongly lineated (L>S) defined by stretched hornblende prisms and rodded quartz-feldspar aggregates interspersed with large (2-4 cm) plagioclase and/or K-feldspar augen and locally contains mafic gneiss xenoliths. These features clearly support a metaplutonic origin for at least part of quartzofeldspathic gneiss. These more massive textured rocks are interpreted here to be correlative to hornblende

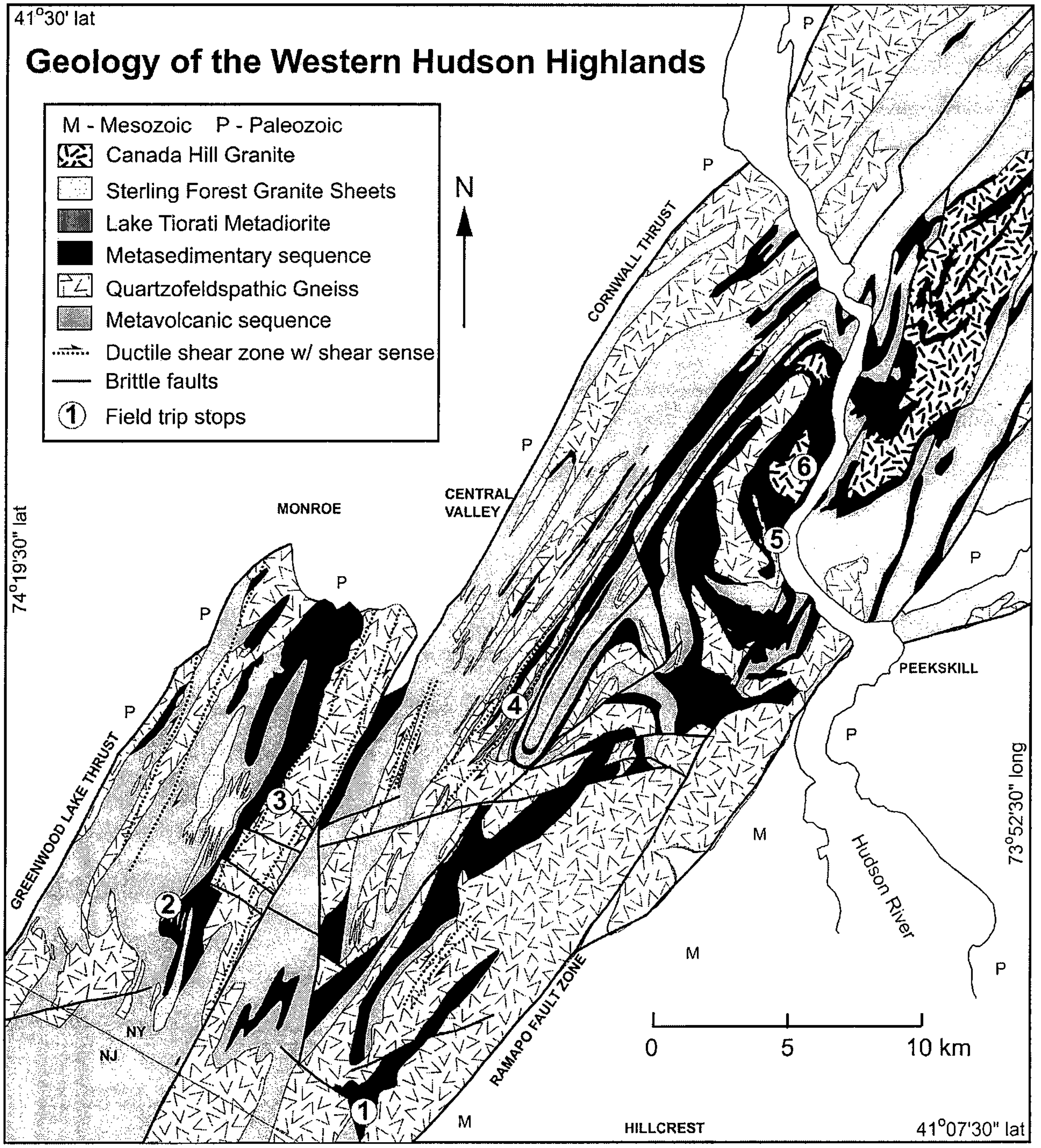

Figure 3. Generalized geologic map of the west central Hudson Highlands showing field trip stops 1-6. Based on geologic mapping of Dodd (1965), Offield (1967), Helenek (1971), Ratcliffe (1992), Valentino (2001); Gates et al., (2001c).

granite gneiss mapped in the Popolopen Lake (Dodd, 1965) and West Point quadrangles (Helenek and Mose, 1984), and Oscawana Lake quadrangles (Ratcliffe, 1992) which has been historically referred to as the Storm King granite (Berkey, 1907; Lowe, 1950). These rocks also correlate with similar metaplutonic hornblende granite gneiss lithologies within the Byram Intrusive Suite in the New Jersey Highlands (Volkert et al., 2000). Preliminary whole-rock geochemical data shows that massive-textured quartzofeldspathic gneiss, Storm King granite gneiss, and the Byram Intrusive Suite all have nearly identical geochemistry, consistent with a protolith that was a strongly A-type granitoid, which further supports their regional correlation (Gorring, et al. 2001; Verrengia and Gorring, 2002).

Current ages constraints on the crystallization age of these metaplutonic rocks based on recent SHRIMP U-Pb ages on igneous cores of zircons range from 1160 to 1230 Ma (Ratcliffe and Alenikoff, 2001; Gates et al., 2001b) (Fig. 4). The quartzofeldspathic gneisses are chemically similar to other metaplutonic rocks of A-type chemical affinity with ages of 1170 to 1210 Ma from other parts of the Grenville orogen including southeastern Canada (Easton, 1986; Lumbers et al., 1990; Davidson 1995) and the Adirondack Lowlands (Wasteneys et al., 1999) as well as the slightly younger AMCG suite (~1145-1155 Ma) in the Adirondack Highlands (McLelland and Whitney, 1990).

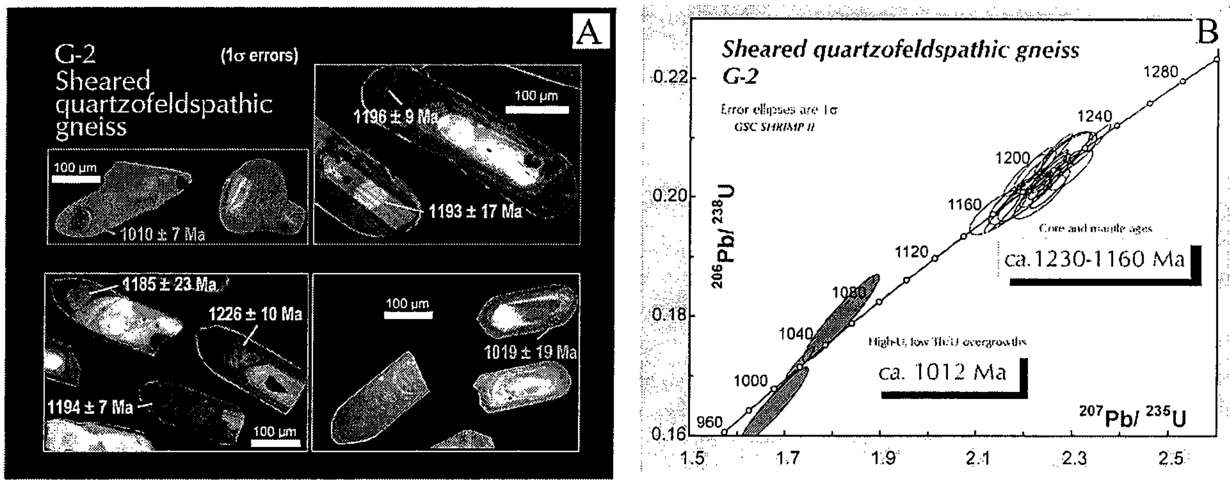

Figure 4. Representative cathodoluminescence images (A) and U-Pb concordia plot (B) from zircons extracted from sheared quartzofeldspathic gneiss within the Indian Hill Shear Zone at Stop 3 analyzed using the SHRIMP II instrument at the Geological Survey of Canada, Ottawa (Gates et al., 2001b).

PRE- TO SYN-OTTAWAN METAMORPHISM AND DEFORMATION

There are at least two (and perhaps three) major deformational events recorded in the crystalline rocks of the Hudson Highlands. The dominant deformational structure of the older event(s) is a penetrative gneissosity that occurs in every unit except the Lake Tiorati Metadiorite, Sterling Forest Granite Sheets, Canada Hill Granite, and late pegmatites (see below). This gneissosity is defined by virtually all minerals but especially by platy and elongate minerals. Biotite, amphibole, sillimanite, and pyroxene are aligned in the strongly foliated quartz-feldspar matrix. Additionally, aggregates of quartz and feldspar define layering in some lithologies. Amphibole and pyroxene clots show similar rotation textures forming δ-porphyroclasts (Passchier and Simpson, 1986). Some pelitic rocks contain garnet-fish structures, and locally, some rocks contain intrafolial asymmetric isoclinal folds 5 to 20 cm thick. The vergence of these folds is consistent in some areas and appears to indicate westward transport. Mesoscopic and megascopic folds produced during this event are recumbent to shallowly reclined. They are tight to isoclinal and commonly asymmetric with the lower limbs sheared out. This asymmetry consistently indicates northwestward transport. The weak and sparse kinematic indicators described above support this shear sense. Thinner layers in these folds contain mesoscopic parasitic folds that are especially well developed on the upper limb. Metamorphism associated with these structures is of hornblende granulite facies and maximum P-T estimates are on the order of 700-750°C and 4±1 kilobar based on mineral assemblages in metapelitic and mafic metavolcanic units (Dallmeyer and Dodd, 1971). Deformation and metamorphism associated with this event is most likely of Ottawan age and is interpreted to have been the result of a Himalayan-type continent-continent collision (Gates et al., in press). However, this does not preclude the possibility of pre-Ottawan deformation events (e.g., Elzeverian, Shawinigan as defined by Rivers, 1997) that could have been obliterated by the Ottawan event. In fact, this is likely the case. Dallmeyer, (1972), Helenek and Mose (1984) and Ratcliffe (1992) report structural evidence (e.g. refolded foliation) for multiple deformation events (e.g. refolded foliation) in the Bear Mountain area and in the eastern Hudson Highlands. Further evidence for a pre-Ottawan deformational history comes from a recent U-Pb SHRIMP zircon crystallization age of 1144 ±13 Ma on the Canopus Pluton in the eastern Highlands that lacks the older fabric elements (Ratcliffe and Aleinikoff, 2001). Structural and geochronologic evidence for multiple, penetrative fabric elements that can be assigned to distinct pre- and syn-Ottawan deformation events has yet to be recognized in the western Hudson Highlands.

EMPLACEMENT OF LATE TO POST-OTTAWAN GRANITOIDS

Granitoids of late- to post-Ottawan age (<1030 Ma) are volumetrically minor in the Hudson Highlands compared to pre-Ottawan rocks, but are important for constraining the late geologic history of the area. They consist of a suite of leucogranite sheets in the Sterling Forest (here called the Sterling Forest granite sheets), Canada Hill Granite (1010 ± 4 Ma; Aleinikoff and Grauch, 1990), Lake Tiorati Diorite (1008 ± 4 Ma; Gates et al., 2001b) and a suite of late, crosscutting pegmatite dikes and mineralized zones (ca. 1000-925 Ma; Gates and Krol, 1998). The Mount Eve Granite (1020 ± 4 Ma; Drake et al., 1991, Gorring et al., in press), located in the far western New Jersey and Hudson Highlands, is part of this suite of late- to post-Ottawan granitoids but will not be visited on this field trip. Similar plutonic granitoid activity of late- to post-Ottawan age has been documented elsewhere in the Adirondacks (ca. 1035 Ma; Lyonsdale Bridge pegmatite; 935 Ma Cathead Mt leucogranite; McLelland et al., 2001) and in the Green Mountain Massif (ca. 960 Ma; Stamford Hill rapakivi granite; Ratcliffe et al., 1991).

Table 1: Representative Major and trace element analyses of Sterling Forest/Harriman State Park granitoids

Unit	Sterling Forest granite sheets					Lake Tiorati Metadiorite						Canada Hill Granite					
Sample	SF-28	SF-29	SF-31	SF-35	SF-36	LT-1	LT-2	LT-3	LT-4	LT-6a	LT-6b	C-5[1]	81-3[2]	13346b[3]	13349[3]	13350[3]	13351c[3]
SiO_2 (wt%)	75.57	76.01	74.97	75.25	74.83	50.66	51.02	49.71	50.94	51.78	49.09	74.30	71.30	74.30	74.50	75.70	75.40
TiO_2	0.04	0.03	0.02	0.05	0.10	0.54	0.49	0.53	0.80	0.57	0.64	0.23	0.14	0.07	0.03	0.02	0.02
Al_2O_3	14.18	13.73	13.41	13.55	13.57	15.63	15.34	14.63	18.54	13.74	12.92	14.00	14.70	14.20	14.60	14.30	13.70
$Fe_2O_{3\,(T)}$	0.41	0.51	0.17	0.47	1.18	9.09	8.36	9.34	7.99	10.12	11.48	0.96	2.10	0.65	0.28	0.22	0.36
MnO	0.02				0.02	0.14	0.16	0.15	0.10	0.16	0.18		0.05	0.02	0.02	0.02	0.02
MgO	0.10	0.07	0.05	0.07	0.20	6.90	7.40	7.91	5.42	8.59	9.90	0.29	0.57	0.28	0.16	0.12	0.10
CaO	1.06	1.32	0.80	0.87	1.39	10.61	12.27	12.41	10.00	11.77	11.86	1.08	0.86	0.95	0.81	1.57	1.13
Na_2O	4.61	3.64	2.73	3.53	3.43	3.66	3.52	3.09	4.38	2.96	2.48	3.15	2.83	3.51	2.76	3.98	3.58
K_2O	3.85	3.94	7.48	5.34	4.89	1.39	0.93	1.19	1.05	0.77	0.80	5.04	6.16	4.68	5.59	3.07	4.53
P_2O_5	0.01	0.01	0.02	0.02	0.02	0.03	0.02	0.05	0.04	0.03	0.03	0.12	0.10	0.13	0.10	0.08	0.07
Total	99.86	99.26	99.65	99.15	99.63	98.65	99.51	99.01	99.26	100.48	99.38	99.17	98.81	98.79	98.85	99.08	98.91
La (ppm)	7.2	7.5	9.2	5.9	35.0	14.7	4.5	34.0	5.8	13.7	8.6		51				
Ce	15.5	10.5	13.2	9.9	67.1	28.6	9.6	54.1	15.3	34.3	22.5		110				
Pr	2.1	1.3	1.6	1.3	7.3	3.5	1.7	5.1	2.4	5.1	3.1		20				
Nd	7.0	3.0	4.1	3.4	24.8	11.6	5.8	15.5	10.3	21.0	12.4		54				
Sm	1.94	0.35	0.54	0.64	4.19	2.31	1.51	2.47	2.87	5.22	3.48		<10				
Eu	0.23	0.45	0.67	0.35	0.64	0.75	0.57	0.62	0.81	1.03	0.86		<2				
Gd	2.43	0.51	0.63	1.20	3.94	2.72	1.93	3.14	3.35	5.47	4.09		10				
Tb	0.56	0.08	0.09	0.30	0.46	0.49	0.39	0.50	0.65	1.00	0.79		<20				
Dy	4.22			2.32	1.82	3.16	3.04	2.79	4.13	6.06	4.75		14				
Ho	1.08	0.06	0.06	0.61	0.36	0.64	0.54	0.60	0.89	1.40	1.19		<4				
Er	3.48	0.47	0.41	1.87	1.13	1.80	1.51	1.72	2.28	3.44	3.02		8				
Tm	0.67	0.07	0.05	0.33	0.15	0.27	0.24	0.26	0.42	0.70	0.62						
Yb	5.66	0.40	0.25	2.22	0.92	1.88	1.53	1.59	2.41	4.30	4.03		7				
Lu	1.00	0.06	0.03	0.36	0.15	0.30	0.23	0.27	0.39	0.74	0.72						
Sr	21	53	74	30	60	195	150	158	181	147	106		150				
Ba	22	113	334	97	224	247	71	170	79	107	75		630				
Cs	0.15	0.20	0.71	0.38	0.36	0.17	0.15	0.22	0.09	0.04							
Rb	133	74	139	125	163	27.5	10.6	22.6	13.9	8.8	8.0						
U	4.88	0.96	0.67	2.45	6.42	0.23	0.41	0.14	0.14	0.26	0.35		7.79				
Th	3.12	1.06	2.20	7.99	30.3	0.88	0.81	1.42	1.42	0.83	0.95		41				
Y	33.7	1.6	3.0	20.6	11.6	18.2	14.4	16.5	24	40.2	34.7		48				
Zr	22	50	19		134	29	22	25	43	40	28						
Hf	0.29	1.72	0.19	1.14	3.67	0.69	0.73	0.58	1.17	0.98	0.75						
Nb	15.1	0.6	0.2	0.5	0.4	1.7	1.0	1.1	3.0	3.5	3.5		4				
Ta	0.98	0.19	0.06	0.01	0.01	0.14	0.13	0.09	0.38	0.33	0.36						
Sc	3.6	0.4	2.2	5.4	1.9	45.0	50.6	51.7	32.1	52.4	53.6		8				
Cr	1.8	1.9	2.1	2.2	3.2	41	91	135	198	137	133		12				
Ni	4.4	2.5	2.2	1.4	2.3	56	65	160	64	73	99		8				
Co	1.4	1.2	0.4	0.8	1.2	34	36	49	31	40	50		3				
V	5.3	7.5	5.2	5.1	9.4	136		220	271	190	208		12				

Major elements, Sr, Ba, Zr, Y, and Sc by ICP-OES at Montclair State University; all other elements by ICP-MS at Binghamton University or INAA at Cornell University

[1] data from Helenek and Mose (1984); [2] Aleinikoff and Grauch (1990); and [3] Ratcliffe (1992)

Sterling Forest Granite Sheets

Recent mapping in the Monroe and Sloatsburg quadrangles by Valentino et al. (2001) has identified a series of leucocratic granite sheets, primarily occurring west of the NY Thruway in the Sterling Forest section of Harriman State Park, that intrude pre-Ottawan rocks of the metavolanic and metasedimentary lithofacies and the quartzofeldspathic gneiss unit. Jaffe and Jaffe (1973) recognized these rocks in the Monroe quradrangle and mapped them as alaskite bodies. Offield (1967) also mapped isolated occurrences of this lithology immediately to the east in the Greenwood Lake quadrangle. The granite is typically medium to coarse grained, locally megacrystic, and lacks penetrative deformational fabrics. However, locally granite sheets are foliated where intersected by later ductile shear zones and thus, clearly are slightly pre- or syn-kinematic to this event. Currently there are no radiometric age constraints on this important unit.

The granite sheets are leucocratic, with K-feldpspar, quartz, plagioclase, only minor (<5%) hornblende and/or biotite, and accessory apatite, zircon, and titanite. The texture is equigranular with subhedral to anhedral interlocking grains, and locally they contain xenoliths of metasedimentary and metavolcanic lithofacies rocks. Where the granite sheets are mylonitic, the contact with the quartzofeldspathic gneiss is difficult to determine. The sheets range in thickness from 5 to 200 m and typically strike northeast-southwest and dip moderately to steeply to the southeast parallel to foliation in the surrounding gneiss. Most are laterally continuous for several kilometers. In the central part of Sterling Forest, the granite sheets extend out from two large tabular shaped bodies of granite. These two bodies of granite and sheet appendages occur within core of shallowly plunging, northeast trending, parallel, open antiformal structures that can be traced from the Monroe quadrangle southward.

The Sterling Forest granite sheets are high SiO_2 (~75%), leucocratic granites with <5% modal mafic minerals (Table 1; Fig. 5A). They are metaluminous to slightly peraluminous (ASI = 0.95 to 1.1) and have highly variable K_2O/Na_2O (0.3 to 3.3) reflecting variability in the modal abundance of K-feldspar or Na-plagioclase as the dominant feldspar. These rocks are divided into three chemically distinct groups based on REE patterns (Fig. 5B and C). The first group is characterized by LREE-enriched, HREE-depleted patterns with moderately negative Eu anomalies (Eu/Eu* = 0.50 to 0.7) (Fig. 5B). The second group has a distinctive concave upward, "dished" MREE-depleted, HREE-enriched pattern with moderately negative to neglible Eu anomalies (Eu/Eu* = 0.35 to 1) (Fig. 5B). The third group is defined by very low total REE's, strong LREE enrichment, depleted and flat MREE to HREE, extremely positive Eu anomalies (Eu/Eu* up to 3.5) (Fig. 5C), and relatively high Sr and Ba concentrations (Table 1) relative to the other two groups. Group 1 granite sheets are best interpreted as partial melts of plagioclase-free source rocks with abundant residual amphibole $\pm$ garnet coupled with fractional crystallization of quartz + feldspars ± trace element-rich accessory phases (e.g., zircon, apatite, monazite, allanite). The garnet-bearing, plagioclase-free source mineralogy implies melt generation probably occurred at deep crustal levels probably involving source rocks of mafic to intermediate compositions. In comparison, Group 2 granite sheets clearly were generated by partial melting of garnet-free source rocks and hence melt generation probably occurred at shallower crustal levels. Group 3 granite sheets most likely represent rocks that accumulated feldspar, perhaps by some sort of filter pressing mechanism that extracted granitic melts during emplacement. These chemically distinctive groups of granite sheets have similar field relations and appear to be part of the same magmatic event, thus crustal melting apparently occurred at various crustal levels. On tectonic discrimination diagrams, the Sterling Forest granite sheets plot scattered along the boundary between fields for syn-collisional and volcanic arc granitoids (Figs. 5D-E).

Canada Hill Granite

The Canada Hill Granite (Berkey and Rice, 1919; Lowe, 1950; Helenek and Mose, 1984) is a distinctively white to blue-gray, coarse-grained leucogranite that occurs as small plutons, sheets, pods, and stringers almost exclusively within metapelitic gneisses of the metasedimentary lithofacies in the northeastern part of the Hudson Highlands (Fig. 3). The largest masses of this unit occur on the eastern side of the Hudson River in the vicinity of Canada Hill in the West Point quadrangle, where it was originally mapped and defined by Berkey and Rice (1919) and again formalized as a distinct, mappable unit by Helenek (1971). Lowe (1950) and Dodd (1965) also recognized this unit to the southwest in the Popolopen Lake quadrangle as well as by Ratcliffe (1992) to the east in the Oscawana Lake quadrangle. The Canada Hill granite is almost always associated with migmatitic host rocks.

The Canada Hill Granite is composed of quartz, white K-feldspar, and white to gray plagioclase in roughly equal proportions. Biotite is ubiquitous as the mafic phase with accessory amounts of sphene, apatite, and zircon. Garnet is locally abundant, especially near contacts with the enclosing migmatites and is interpreted to represent undigested xenocrysts derived from the metapelites. It is predominantly massive textured with only local development of a weak foliation. The orientation of the sheets and pods of Canada Hill Granite parallel the foliation in the surrounding metapelites and contacts are generally gradational and migmatitic, except locally where the granite clearly truncates foliation in the migmatitic metapelites. Aleinikoff and Grauch (1990) obtained a conventional, multigrain, TIMS U-Pb zircon crystallization age of 1010±6 Ma for the Canada Hill Granite and 1010±4 Ma for associated thin leucosome from surrounding migmatitic metapelitic gneiss from the same locality.

The Canada Hill Granite has long been interpreted as a late, synmetamorphic (anatectic) granite derived from partial melting of the surrounding metapelitic layers in the metaturbidites of the metasedimentary lithofacies (Lowe, 1950; Helenek and Mose, 1984; Ratcliffe, 1992). The intimate association of Canada Hill Granite and the

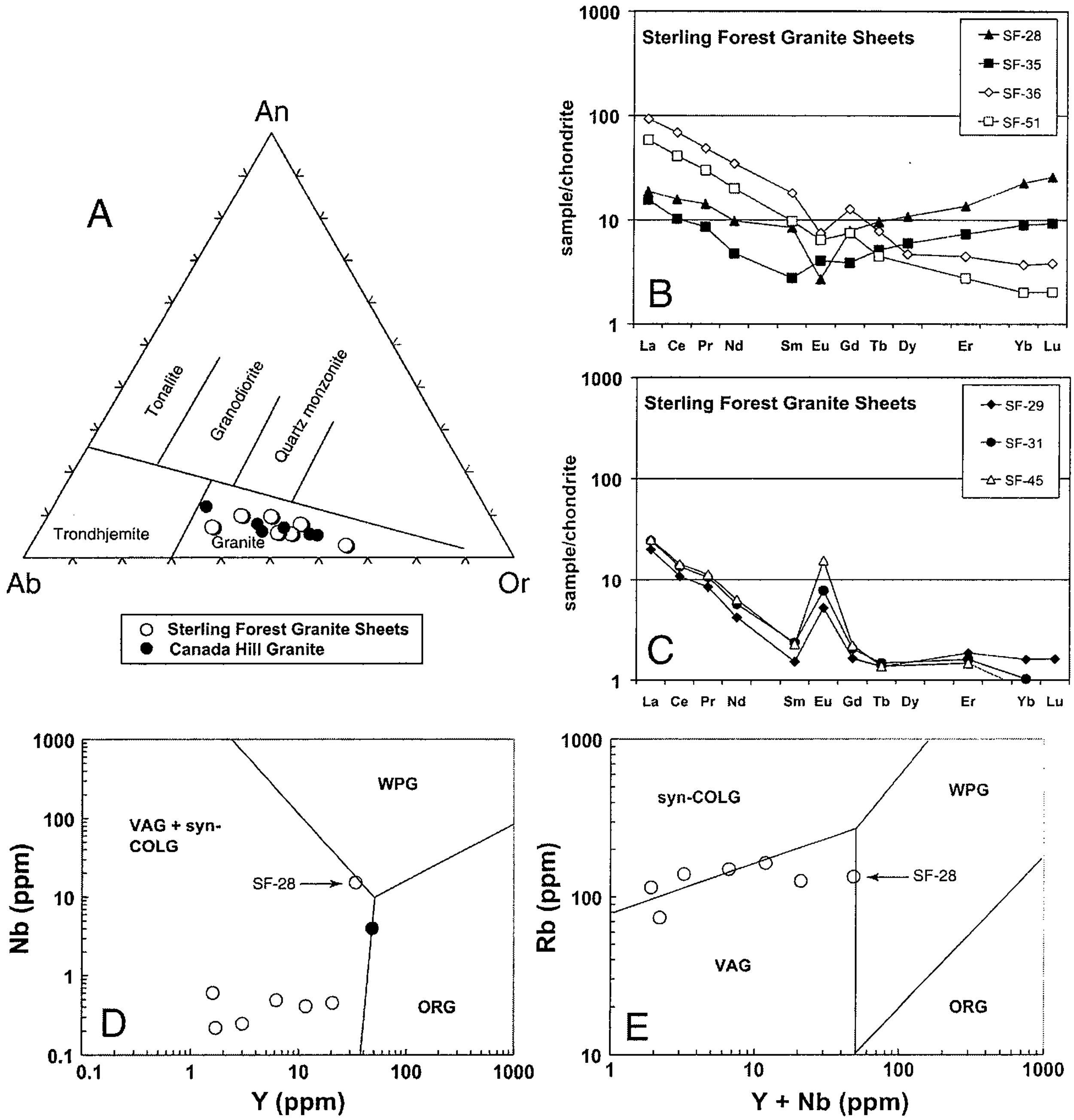

Figure 5. Geochemical plots for Sterling Forest granite sheets and the Canada Hill Granite. (A) Normative Ab-An-Or classification diagram (O'Connor, 1965). (B) and (C) REE plots showing three distinctive REE patterns within the Sterling Forest suite. Sample SF-28 is from field trip Stop #2. (D) and (E) are granitoid tectonic discrimination diagrams (Pearce et al., 1984). VAG = volcanic arc granitoid; syn-COLG = syn-collisional granitoid; WPG = within-plate granitoid; and ORG = ocean ridge granitoid. Chondrite normalization factors are from Masuda et al., (1973). Canada Hill data from Helenek and Mose (1984) and Ratcliffe (1992).

migmatites on a regional scale and the similarity of leucosome compositions and U-Pb zircon ages in migmatites with the Canada Hill support a petrogenetic link between them. Available geochemical data on the Canada Hill Granite consists of several analyses reported in Helenek and Mose, (1984), Aleinikoff and Grauch (1990); and Ratcliffe (1992) that are compiled in Table 1. The Canada Hill Granite is a high SiO_2 (71 to 75 wt%), very low

FeO_T (generally <1 wt%), peraluminous, corundum-normative, biotite granite. These major-element chemical characteristics along with a high initial $^{87}Sr/^{86}Sr$ ratio of 0.7186±0.0017 reported by Helenek and Mose (1984) provides additional support for a metapelitic source rock (e.g., S-type granite) for the Canada Hill Granite. We are currently conducting a more detailed geochemical study of the Canada Hill Granite that will elucidate more precisely the petrogenesis of this unit and it's bearing on the late Ottawan history of the area.

Lake Tiorati Metadiorite

The Lake Tiorati Metadiorite is a coarse- to very coarse-grained black and white speckled rock composed of sodic-plagioclase, pyroxene (both clinopyroxene and orthopyroxene), hornblende, and biotite locally. The type locality and location of the largest body (~0.5 km wide and ~5 km long) is along the western shores of Lake Tiorati in the central part of Harriman State Park within the Popolopen Lake quadrangle (Fig. 3) and was originally described by Lowe (1950) and mapped by Dodd (1965) as a coarse grained amphibolite ("Amphibolite II"). A few smaller, lens-shaped bodies occur a few kilometers to the southwest in the northeast corner of the Sloatsburg quadrangle recently mapped by Valentino et al. (2001). The metadiorite grades to lower pyroxene, gabbroic anorthosite compositions locally. Texture ranges from granoblastic to foliated and mylonitic with S-C fabric and rotated porphyroclasts. The metadiorite also locally contains xenoliths of mostly mestasedimentary lithofacies rocks. Recent SHRIMP U-Pb dating of small, subhedral zircons with minimal zoning obtained from undeformed metadiorite from the type locality yielded a cluster of concordant ages averaging 1008 ±4 Ma (Fig. 6). This is interpreted to be the crystallization age of the Lake Tiroati Metadiorite

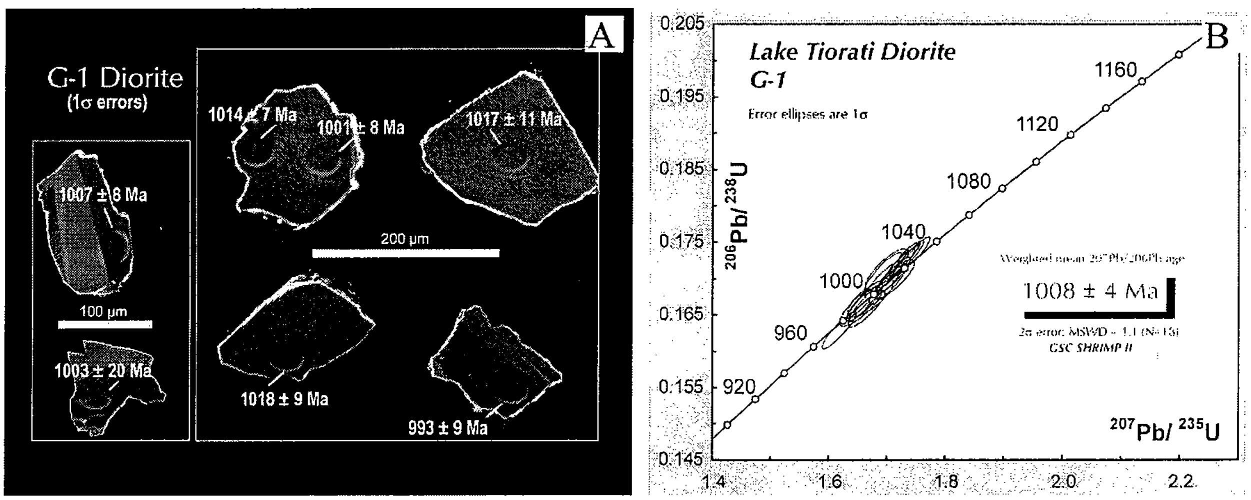

Figure 6. Representative cathodoluminescence images (A) and U-Pb concordia plot (B) from zircons extracted from the Lake Tiorati Metadiorite from Stop 4c analyzed using the SHRIMP II instrument at the Geological Survey of Canada, Ottawa (Gates et al., 2001b).

Major element chemistry of coarse-grained, relatively undeformed samples of the Lake Tiorati Metadiorite indicate they are uniformly mafic plutonic rocks that have moderate to strong calc-alkaline geochemical signatures (Table 1; Fig. 7A). REE patterns of most samples are weak to moderately LREE-enriched (La/Yb_N = 1.5 to 5) and slightly concave upward or "dished", MREE-depleted patterns with little to no HREE-depletion (Fig. 7B). They also have variable negative Eu anomalies (Eu/Eu* = 0.6 to 1.0). The mafic, calc-alkaline composition, relative strong negative Eu anomalies and slight MREE depletions in some samples suggests that significant plagioclase ± hornblende crystallization was important in the petrogenesis of these rocks before final emplacement. The lack of strong HREE and Y depletions relative to other trace elements indicates mantle melting occurred at relatively shallow depths above the garnet stability field (e.g. <65 km). All samples have very strong HFSE depletions and on plot well within volcanic arc fields on tectonic discrimination diagrams characteristic of calc-alkaline rocks associated with subduction zones (Figs. 7C). We interpret the arc signature in these rocks to have been inherited from lithospheric mantle sources that had been metasomatized by prior subduction events and/or extensive crustal contamination during emplacement in the crust.

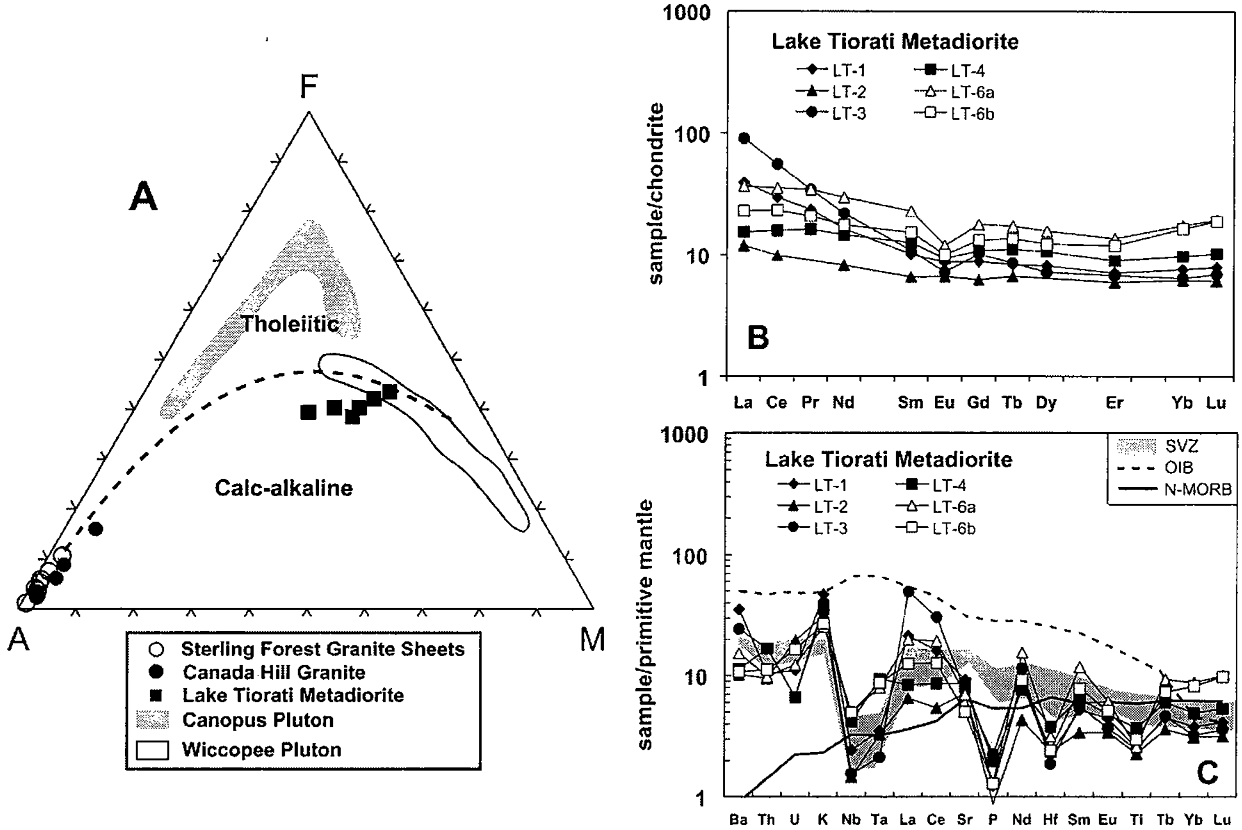

Figure 7. (A) AFM diagram showing the calc-alkaline affinity of the Lake Tiorati Metadiorite in comparison with other Mesoproterozoic mafic plutonic rocks (Canopus and Wiccopee Plutons) from the eastern Hudson Highlands (Ratcliffe, 1992). (B) REE patterns and (C) multi-element diagrams showing the strong volcanic arc chemical signature (LREE-enriched, HFSE-depleted) of the Lake Tiorati Metadiorite. OIB is average oceanic island basalt; N-MORB is average normal mid-ocean ridge basalt; and SVZ is field for Quaternary mafic lavas from the Andean Southern Volcanic Zone (Hickey et al., 1986; López-Escobar et al., 1993). OIB, N-MORB, and normalizing factors are from Sun and McDonough (1989) and Masuda et al., (1973).

Late Pegmatite Dikes

Gates et al. (2001b) recognized two generations of pegmatite dikes in this part of the Hudson Highlands. Early dikes are white and contain K-spar, quartz, muscovite, and garnet locally. They are largely parallel to subparallel gneissic foliation (concordant), commonly boudinaged, and contain internal foliation and deformed grains. Thickness ranges from 10cm to 1m. Many are associated with the Sterling Forest granite sheets and thus, are probably pre- or syn-deformational with the late ductile shearing event. The late dikes are pink, and very coarse grained with K-spar, quartz, and locally muscovite, hornblende, magnetite, pyroxene, titanite, and/or garnet depending upon the rock intruded. They are highly discordant, commonly within brittle faults, and contain xenoliths of fault rocks. They exhibit no deformational fabric. Thickness ranges from 1m to 10m. They are locally associated with small granite bodies. Dodd (1965), Offield (1967), Jaffe and Jaffe (1973), and Ratcliffe (1992) have also described similar late, cross-cutting pegmatites throughout the Hudson Highlands. Existing radiometric age dates for late pegmatite dikes include a hornblende $^{40}Ar/^{39}Ar$ ages of 923 ± 2.8 Ma reported by Gates and Krol (1998) and conventional TIMS U-Pb zircon ages of 964 to 1023 Ma obtained by (Aleinikoff et al., 1982).

LATE TO POST-OTTAWAN STRUCTURES

Recent geologic mapping and structural analysis in both the New Jersey and Hudson Highlands has recognized the importance of a late to post-Ottawan, high-grade, ductile shearing event (Gates, 1998; Allers et al., 2001). Similar structures have been recognized recently in the central Adirondacks that may also be of late Ottawan age (Valentino et al., 2001; Solar et al., 2003). This deformation event (D_2) is characterized by a group of anastomosing shear zones across the area (Figs. 2 and 3). These shear zones overprint the structural features associated with the first (and/or second) deformational event(s) (D_1) that is characteristic of the pre-Ottawan rocks (metasedimentary and metavolcanic lithofacies and the quartzofeldspathic gneiss unit). The shear zones strike northeast and are either vertical or steeply northwest to southeast dipping. They range from 0.5 to 2 km in thickness though the boundaries are diffuse and difficult to determine in some areas. The shear zones are marked by well-developed type II S-C mylonite (Lister and Snoke, 1986) with shallowly northeast plunging mineral lineations. The dominant lithology within the mylonite is quartzofeldspathic gneiss but some rocks of the metavolcanic and metasedimentary lithofacies are also sheared. Metadiorite also locally forms S-C mylonite constraining the time of emplacement to pre-kinematic with regard to this event. Kinematic indicators within the mylonite include C/S fabric, rotated porphyroclasts, shear bands, asymmetric boudins and flattened asymmetric intrafolial folds. There are well-developed mesoscopic sheath folds with shallow northeast plunge, and megascopic drag folds adjacent to the main shear zone. All kinematic indicators show a consistent dextral strike-slip sense of shear. Minerals within the sheared rocks include amphibole and biotite as well as quartz and feldspar, all of which show plastic deformation but with full recovery. By texture and mechanical response of the minerals (Simpson, 1985), metamorphic conditions must have been upper amphibolite to granulite facies.

Adjacent to the zones are sheath folds and boudins within deformed layered sequences. They are strongly lineated and the structures are extended parallel to the lineations. Mesoscopic gentle to open upright folds also occur adjacent to the shear zones locally. These folds plunge gently from due north to north-northeast. The folds occur in well-layered metavolcanic sequences and within 150 m of the shear zone boundary. They locally appear en echelon. A pervasive steeply northwest-dipping crenulation cleavage occurs throughout the area. It is best developed in the metapelitic and thin layered metavolcanic units. Intersection lineations with the gneissic foliation produced in the early event are generally parallel to the stretching lineations in the mylonite. Late in the movement history, the shear zones became dilational. One to 5 km long mineralized veins occur along the shear zones. The veins parallel the zones but clearly cut the mylonitic foliation with ragged to planar contacts. The veins were progressively filled with salite and scapolite locally followed by magnetite. These zones are also commonly intruded by late pegmatites, some of which contain xenoliths of mineralized rock.

Timing of this ductile shearing event is constrained by recent SHRIMP U-Pb zircon ages on mylonitic rocks within and adjacent to the shear zones (Gates et al., 2001b). The Lake Tiorati Metadiorite is cut by the Fingerboard Mountain Shear Zone and has age of 1008 ±4 Ma (Fig. 6) and thus provides an upper age limit to the deformation in this area. SHRIMP data on zircon rims from the sample of sheared quarztofeldspathic gneiss from within the Indian Hill Shear Zone are not well clustered (range from 1000 to 1060 Ma), but the most concordant data yield ages around 1010 to 1020 Ma (Fig. 4). Late pegmatites that crosscut mylonitic fabric in these shear zones would provide lower age limits, unfortunately there are currently no age constraints on these specific occurrences. As mentioned above, similar late pegmatites have radiometric ages in the range of about 925 to 1000 Ma. Therefore, based on the geochronologic data presently available, this ductile shearing event is constrained to have occurred between ~1010 and 925 Ma, with the lower limit being relatively uncertain.

IMPLICATIONS FOR GRENVILLE TECTONICS

One of the principal tectonomagmatic events in the Grenville orogen during the late Mesoproterozoic was the Ottawan Orogeny (~1090–1030 Ma; e.g., McLelland et al., 1996; 2001). The Ottawan Orogeny is thought to have been a Himalayan-style continental collision event with associated crustal thickening, high-grade metamorphism, ductile nappe-style folding in the southeast (e.g., in the Central Granulite Terrane, Adirondack Highlands, and Appalachian massifs) and brittle northwest-directed thrusting farther west (e.g., Grenville Front Tectonic Zone and Central Metasedimentary Belt) in the orogen. This collisional event is thought to be related to the acrretion of various continental masses to form the supercontinent Rodinia (Hoffman, 1988; Dalziel, 1991; Borg and DePaolo, 1994). Although the timing of peak Ottawan orogenesis varies spatially, this event severely affected most rocks older than ~1060 Ma throughout much of the Grenville orogen (e.g., McLelland, 1996, 2001; Aleinikoff et al., 2000). The age and field relations of the Lake Tiorati Metadiorite and the Canada Hill Granite suggests that penetrative deformation assigned to the Ottawan Orogeny as classically defined was finished prior to ~1010 Ma in the Hudson Highlands. Supporting evidence for this statement also comes from the undeformed Mount Eve Granite suite (Gorring et al., in press) which places a lower limit of ~1020 Ma for penetrative Ottawan metamorphism and deformation in the far western portion of the New Jersey/Hudson Highlands.

The presence of large-scale, vertical strike-slip ductile shear zones that cross-cut rocks of ~1010 Ma indicates that the late- to post-Ottawan history in the Hudson Highlands is characterized by a high-grade, dextral transpressional shearing event that occurred between ~1010 to 925 Ma. This event likely represents final adjustments of the amalgamated Rodinian supercontintent and/or another accretionary event that must have occurred far to the north of the Hudson Highlands. A collision in the area of the Canadian Appalachians and Scandinavia may have generated tectonic escape (e.g., Tapponnier et al., 1982; Burke and Sengor, 1986) of eastern Laurentia to the south along large dextral strike-slip faults (Fig. 8A). The strike-slip environment could explain the temporal association of the late- to post Ottawan granitoid suite described here (Canada Hill Granite, Lake Tiorati Metadiorite, Mount Eve Granite). Collectively these granitioids consist of small, dispersed plutonic bodies that form a volumetrically minor, chemically diverse group that ranges from A- and S-type granites to calc-alkaline, I-type diorite. Localized crustal heating due to upwelling asthenosphere associated with localized extension and/or transtension in the overall dextral transpressional regime could explain the small volumes and limited areal extent of these granitoids (Fig. 8B). A similar transpressional tectonic model has been proposed by Speer et al. (1994) to explain the occurrence of small volume, chemically diverse plutonic suites of Alleghenian age in the southern Appalachians. This type of model may explain similar small volume occurrences of late- to post-Ottawan (ca 1030–930 Ma) granitoids elsewhere in the Grenville orogen, particularly in the Adirondacks (e.g., Lyonsdale Bridge and Cathead Mountain pegmatites; McLelland et al., 2001) and the Green Mountain massif (e.g., Stamford Hill rapakivi granite; Ratcliffe et al., 1991).

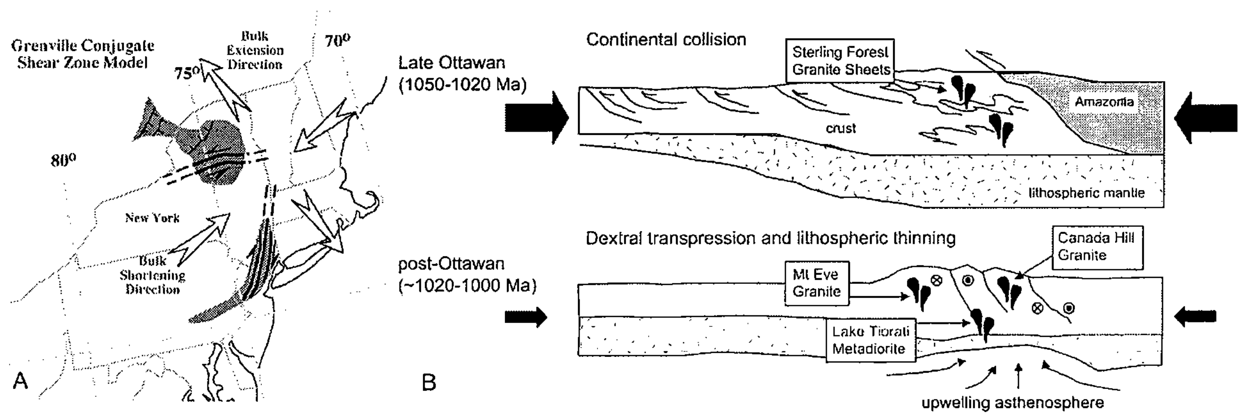

Figure 8. (A) Regional map view and (B) cross-sectional view of model for late to post-Ottawan tectonics in the Hudson Highlands. Diagrams modified from McLelland et al., (1996) and Gates et al., 2001a; in press.

CONCLUSION

The late- to post-Ottawan (<1030 to 925 Ma) geologic history of the west central Hudson Highlands is characterized by large-scale, high-grade ductile shearing, migmatization, and the emplacement of a chemically diverse suite of granitoid plutons. The ductile shear zones are large (0.5 to 2 km wide, 2-10 km long), subvertical to vertical, and all kinematic indicators (e.g., S-C fabrics, rotated porphyrclasts) are consistent dextral strike-slip deformation. Timing of deformation on these shear zones is currently broadly constrained to an upper limit of ~1010 Ma based on the SHRIMP U-Pb zircon ages on the Lake Tiorati Metadiorite and on metamorphic rims on zircons from a sample of sheared quartzofeldspathic gneiss and a rough lower limit of 925 Ma based on hornblende $^{40}Ar/^{39}Ar$ age obtained from an undeformed, late pegmatite. A suite of pre- and syn-deformational granitoid plutons with diverse geochemical characteristics we also emplaced associated with this shearing event. They consist of the Sterling Forest Granite Sheets, the Canada Hill Granite (1010 ± 4 Ma; Aleinikoff and Grauch, 1990), the Lake Tiorati Metadiorite (1008 ± 4 Ma; Gates et al., 2001b) and late, crosscutting pegmatite dikes and mineralized zones (ca. 1000-925 Ma; Gates and Krol, 1998). The Mount Eve Granite (1020 ± 4 Ma; Drake et al., 1991, Gorring et al., in press) is also part of this suite of late- to post-Ottawan granitoids. Dextral strike-slip shearing and granitoid emplacement is interpreted here to have resulted from a tectonic escape mechanism due to late- to post-Ottawan adjustments within the newly amalgamated Rodinian supercontinent and/or a separate, late accretionary event to the north of the study area.

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ROAD LOG

MILEAGE

0.0 From Reeves Meadows Visitor Center parking lot, Harriman State Park, turn left out of the parking area onto Seven Lakes Drive.

1.5 Turn **LEFT** onto NY Rt. 17 at the T-intersection and traffic light in Sloatsburg. Continue on NY Rt. 17 through the town of Sloatsburg.

3.7 Stay in left lane and follow signs for NY Rte 59.

4.0 Continue straight ahead on NY Rt. 59 East. Large roadcuts off to the right (southbound side of NY Thruway) are hornblende granite gneiss and mafic to intermediate metavolcanic gneiss.

4.7 Turn **LEFT** on Torne Valley Road (County Road 95) and travel north. Large outcrops of hornblende granite gneiss on right (east) side of road (see Fig. 9A).

5.4 Pull over on left (west) side of road into gravel parking lot of the "H. Pierson Mapes/Flat Rock County Park" along the bank of the Ramapo River.

STOP 1: RESIDUAL MIGMATITIC METATURBIDITE, DIATEXITE AND GRANITE SHEETS

Stop 1a: The first of two substops is a spectacular riverbed exposure of typical migmatitic gneiss found in the Hudson Highlands. **No hammers please.** Pavement exposure of migmatitic metaturbidite composed of steeply SE-dipping 5-10 cm-thick alternating layers of metapelite and metapsammite (Fig. 9B). Metapelitic layers are 3-5 cm thick with cm-scale, mesescopically poikolitic garnet porphyroblasts draped by matrix minerals that form sinistral strain shadow tails defined by aggregates of Qtz+Bt+Pl+Sil. The mineral composition of the metapelite layers are consistently residual suggesting significant melt production and loss from these rocks.

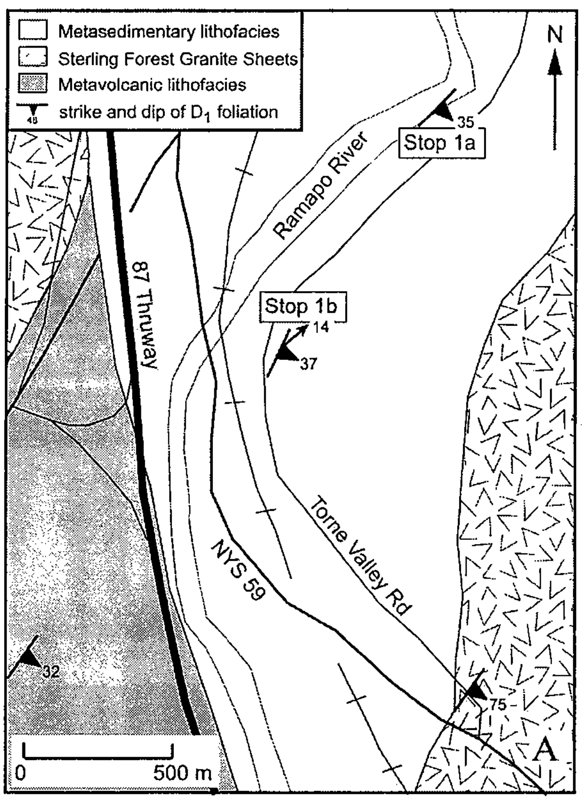


Figure 9. (A) Geologic map showing location of Stop 1a and 1b. (B) Pavement exposure of migmatitic metaturbidite aong the Ramapo River at Stop 1a. D. Valentino's legs for scale.

Stop 1b: Walk south along road to pavement surfaces (~0.1 miles) and vertical roadcut (~0.2 miles) exposed on the left (east) side of the road (Fig. 9A). These outcrops are the along strike continuation of the migmatitic metaturbidite of Stop 1a. These rocks are similar to those of the stream pavement, except for the presence of residual diatexite (Grt+Bt+Pl+Qtz+Sil) and concordant- to weakly discordant cm-scale granite sheets (best seen in the pavement exposures). Where present, diatexite shows local disruption of the protolith and stromatic migmatite structure (seen at Stop 1a) that apparently formed during syntectonic melting and melt movement within the diatexite. Note the local pinch-and-swell of granite sheets and the fabric boudinage of diatexite gneiss (quartzite in the interboudin partition). Residual diatexite is disrupted locally in which the diatexite has formed schollen with concordant granitic composition tails and Grt+Bt-rich melanosomatic drapes at the edges of their long dimension.

6.1 Return back down (south) on Torne Valley Road and turn **RIGHT** onto NY Rte 59 (Orange Ave.).
6.5 Continue traveling West on NY Rte 59 straight through traffic light and then follow signs for NY Rte 17 North.
8.1 Follow exit ramp right for County Road 72, follow Rt. 72 West.
11.2 Turn **RIGHT** at traffic light onto Long Meadow Road. You will see signs for Sterling Forest Park.
14.6 Small roadcut on left (west) side of metavolcanic amphibolite.
15.4 Old Forge Road enters at very sharp angle from left (west) side.
15.5 Pull over on right (east) side of road on decent gravel pad opposite roadcut of prominent pink granite.

STOP 2: STERLING FOREST GRANITE SHEETS

This roadcut along northwest side of Long Meadow Road near the Sterling Forest Park headquarters exposes a fine example of the late- to post-Ottawan suite of pink, granite sheets found in the Hudson Highlands (Fig. 10). These sheets are very leucocratic (~75 wt% SiO_2), composed of almost entirely quartz, K-feldspar, and plagioclase, with only small amounts (<5%) of hornblende ± biotite with accessory apatite, titanite, and zircon. At this locality, the sheet has a medium-grained, equigranular igneous texture and shows no evidence of deformational fabric. However, locally these granite sheets are foliated where intersected by late-stage, ductile shear zones and thus, are clearly pre- or syntectonic with the shearing event. This particular sheet is one of several, 10-100 m thick, finger-like bodies that extend both southward and northward several kilometers from the main plutonic masses at Hogback Mountain (to the north) and Bill White Mountain (to the south). Here, the sheet is about 20 m thick, strikes N20E and dips ~65° to the southeast and has intruded parallel to foliation in the surrounding gneisses. It intrudes amphibolites and intermediate gneisses of the metavolcanic unit (contact observed at the north end of the outcrop) and metapelitic gneisses of the metasedimentary lithofacies (exposed across the road a short distance into the woods on the other side of the road). The granite sheet exposed here (sample SF-28) has a distinctly "dished" MREE pattern, a moderately strong negative Eu anomaly (Eu/Eu* = 0.35), high HREE contents (~20x chondritic) and very low Ba and Sr concentrations (~20 ppm) (Fig. 5B and Table 1). These chemical characteristics indicate that amphiboles and feldspars were important phases in the petrogenesis of this particular granite. The data is consistent with partial melting of garnet-free, mafic amphibolitic source rocks and/or fractional crystallization of amphibole + plagioclase ± K-feldspar at shallower crustal levels.

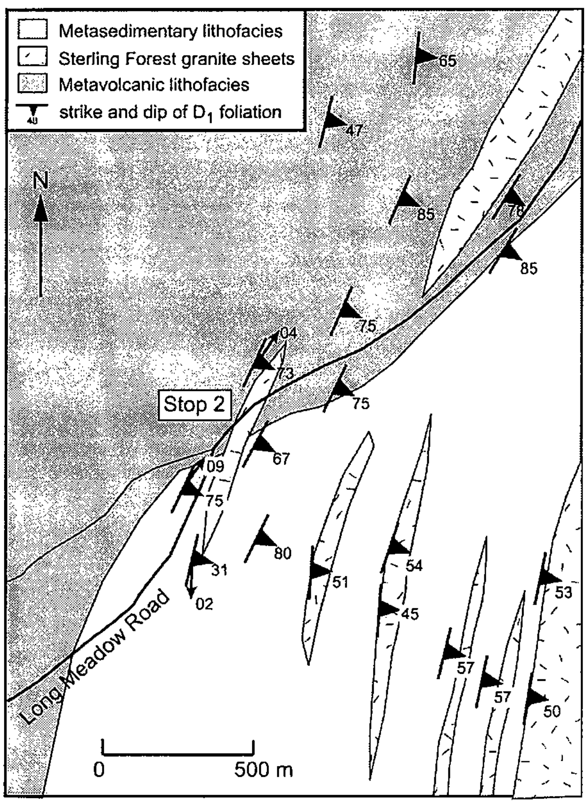


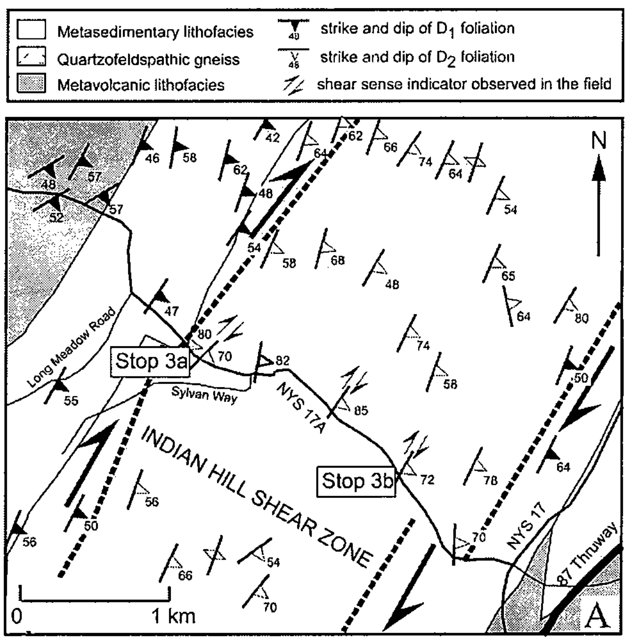
Figure 10. Geologic map showing location of Stop 2.

19.1 **RIGHT** onto NY Rte 17A heading east (two-lane divided highway).
19.2 Large roadcuts of calc-silicate gneisses on opposite (north) side of 17A.
19.6 Make U-turn at Sylvan Way and go back on 17A West. Roadcut on right (north) side and in median is rocks seen at Stop 3.

19.9 Drive past west end of roadcut ~0.1 mile and pull over on wide shoulder. **BE CAREFUL!! Fast moving traffic and limited sight distance.**

STOP 3: INDIAN HILL SHEAR ZONE

Roadcuts on north side and in median of NY Rte 17A afford an excellent view of highly sheared quartzfeldspathic gneisses within the Indian Hill Shear Zone (Fig. 11). The Indian Hill Shear Zone is one of several deformation zones in an anatomizing system of ductile shear zones that occur in the Hudson Highlands (Fig. 2). Timing of ductile deformation on the Indian Hill Shear Zone is currently constrained (albeit loosely) by recent SHRIMP U-Pb zircon ages from one sample of sheared quartzofeldspathic gneiss within the Indian Hill Shear Zone. The sample yielded zircons with rhythmically zoned igneous cores and clear, unzoned metamorphic rims (Fig. 4a). Analyses of the cores and rims produced two clusters of concordant ages (Fig. 4b). The cores ranged from 1160 to 1230 Ma. The most concordant rims ranged from 1000 to 1060 Ma, yielding an imprecise average of ~1010-1020 Ma. We interpret the zoned cores and associated ages to represent the original igneous history for this rock, and the rims to represent the regional metamorphic overprint, which includes high-grade ductile shearing on the Indian Hill Shear Zone. More rigorous constraints on the timing of ductile shearing in this area await additional U-Pb SHRIMP zircon geochronology on rocks within the Indian Hill Shear Zone as well as the Sterling Forest Granite sheets (upper limit), and cross-cutting, late pegmatites (lower limit).



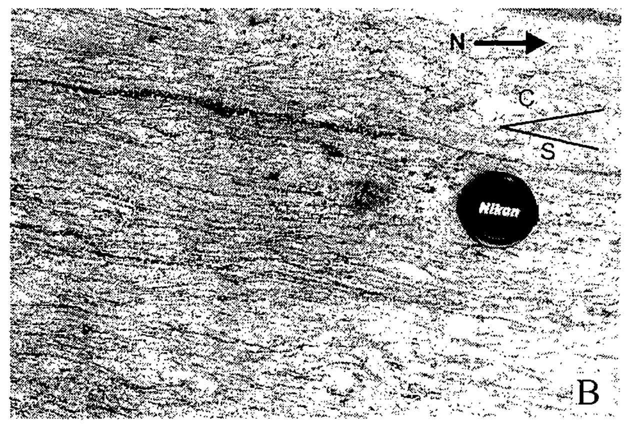


Figure 11. (A) Geologic map showing location of Stops 3a and 3b. (B) Pavement surface of sheared quartzo-feldspathic gneiss within the Indian Hill Shear Zone at Stop 3a showing well developed dextral shear sense indicators (C-S fabrics, asymmetric K-feldspar porphyroclasts).

Stop 3a: Spectacular ductile shear zone structures in are found on the pavement surface on top part of the outcrop in the median strip. The rock is a quartzofeldspathic mylonitic gneiss with thin (10-50 cm) interlayers of amphibolite and garnet-biotite-quartz-plagioclase gneiss locally. The quartzofeldspathic mylonite is well foliated and lineated and composed of plagioclase, quartz, K-feldspar, and biotite. This mylonite exhibits well-developed kinematic indicators including S-C fabric, reverse shear cleavage (RSC), rotated porphyroclasts, and shear bands. These kinematic indicators show a consistent dextral shear sense. The width of the zone and low S-C angle indicate significant offset. Locally there are small sinistral shear zones that crosscut the main foliation and are interpreted to be conjugate. The mylonitic foliation is commonly folded into open to tight shallowly northeast-plunging asymmetric folds. There are pegmatite dikes that are parallel to mylonitic foliation and which commonly displays pinch and swell. There are also late pegmatites that form in "gaps" in the mylonite. Cutting the mylonite at this locality is a prominent is a late pegmatitic dike (~2-3 m thick) composed of coarse-grained granite with large crystals of hornblende that form radiating and linear aggregates. It is exhibits no deformation fabric and clearly postdates the ductile deformation of the quarztofeldspathic gneisses. Unfortunately, there are no radiometric age constraints for the pegmatite.

20.2 Proceed west on NY Rte. 17A and immediately get in left lane. **Make U-turn** at Long Meadow Road and head east on 17A. Small roadcuts of mylonitic quartzofeldspathic gneiss within the Indian Hill Shear Zone are seen along the north side of the road east of Stop 3b.

21.6 Carefully make **U-turn** at the bottom of hill at intesection with NY Rte. 17. Go back up hill on NY Rte 17A West.

21.8 Roadcut of quartzofeldspathic gneiss.

22.1 Pull over on shoulder of highway just past (north) of roadcut.

Stop 3b: This small roadcut again displays highly-sheared quartzofeldspathic gneisses and thin (10-50 cm) layers of amphibolite and garnet-biotite-quartz-plagioclase gneiss on both pavement surfaces and vertical cuts.

22.5 Continuing west on NY Rte 17A, make a **U-turn** at Sylvan Way and then proceed back on 17A east.

23.4 Intersection with NY Rte 17 again, this time continue straight on through intersection. NY Rte 17A becomes County Road 106 and enter Harriman State Park.

28.5 Enter Kanawauke Circle and go ¾ around and follow Seven Lakes Drive toward Lake Tiorati and Bear Mountain.

30.4 Entrance to Camp Thendara on right. Pull over on right side as much as possible (careful of large rocks that line the road) (see Fig. 12).

<u>Note:</u> If you do this trip yourself, you will have to park about 1 mile to the north at Lake Tiorati Circle or gain permission from Harriman State Park to park along the road.

Walk north ~0.2 miles along Seven Lakes Drive to the blue blaze trailhead on the left (west) side (Fig. 12). Follow the blue trail up the east flank of Fingerboard Mountain for ~0.5 mile to the lean-to shelter near the top. Stop for lunch and enjoy the spectacular mylonite outcrops!!

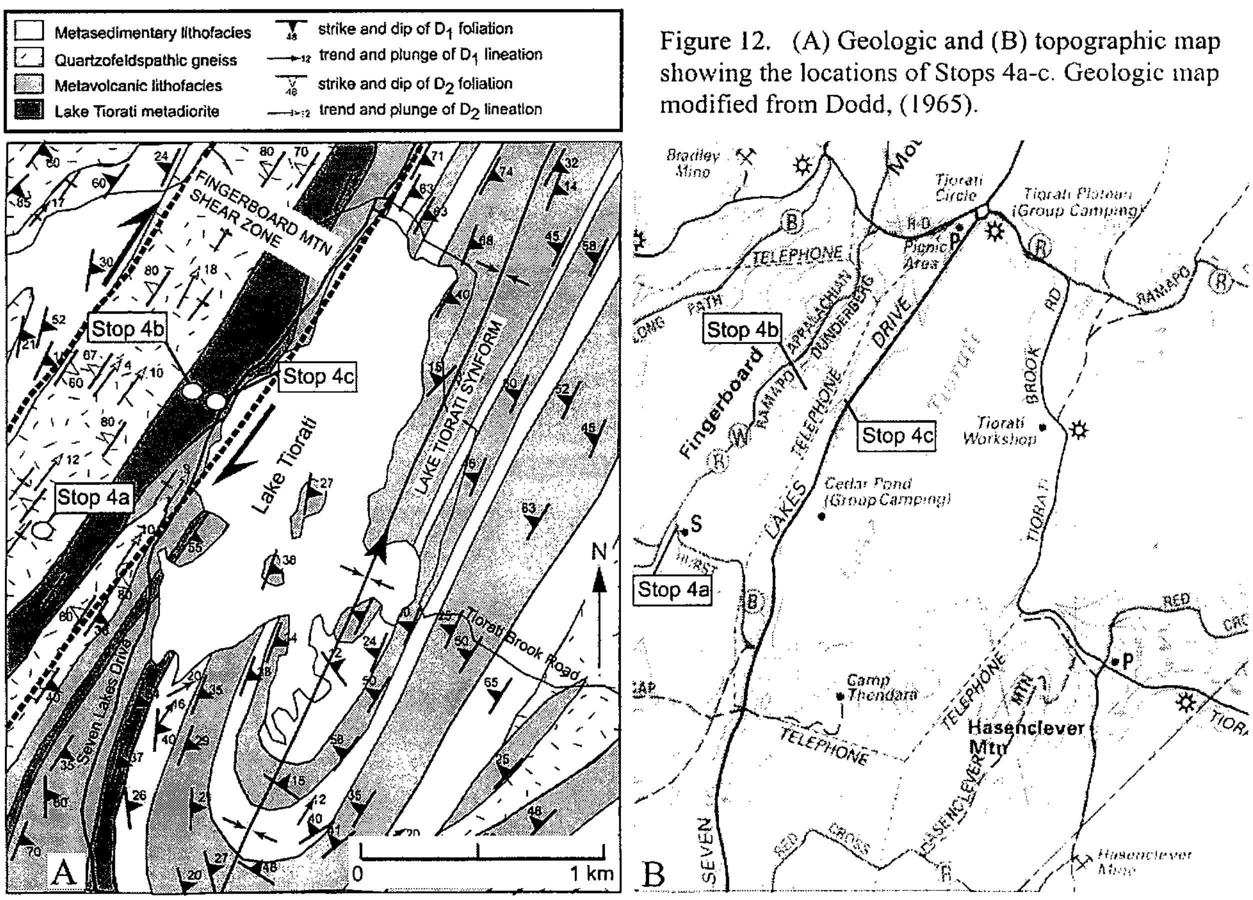


Figure 12. (A) Geologic and (B) topographic map showing the locations of Stops 4a-c. Geologic map modified from Dodd, (1965).

STOP 4: FINGERBOARD MTN SHEAR ZONE AND LAKE TIORATI METADIORITE

The next series of substops will require a moderate walk (~ 2 miles and 300 vertical feet) along hiking trails and finally though some open forest. We will examine another spectacularly exposed ductile shear zone within quartzofeldspathic gneiss along the Appalachian Trail on the crest of Fingerboard Mountain and then look at field relations and chemistry of a sheared mafic metaplutonic rock along the shore of Lake Tiorati. Bring food and water, as we will stop near the top of Fingerboard Mountain to eat lunch.

Stop 4a: Here at the shelter, and for the next ½ mile northward along the Appalachian Trail on the crest of Fingerboard Mountain, a series of nearly continuous pavement surfaces exposes mylonites of another 1- to 2-wide, 10- to 20-km long ductile shear zone. The rock is quartzofeldspathic mylonitic gneiss with mineralogy and structure very similar to that observed in the Indian Hill Shear Zone at Stop 3. Foliation is either vertical or very steeply dipping to the northwest or southeast with shallow plunging (<20° NE) lineation indicating dominantly strike-slip ductile shearing (Fig. 12A). Like the Indian Hill Shear Zone at Stop 3, kinematic indicators (e.g., S-C fabric, rotated porphyroclasts) show consistent dextral shear sense and the very low S-C angle indicates significant offset.

Follow the blue trail above the shelter to the junction with Appalachian Trail. Turn right (north) and walk along the crest of Fingerboard Mountain for about ~0.5 miles (rocks of Stop 4a above are here). Descend about 80 vertical feet into small col and then make a right (east) turn into the woods following the drainage for ~0.1 mile. Ascend slightly up the north flank of the drainage through a series of closely spaced outcrops near the contact of quartzfeldspathic mylonite and amphibolites of the metavolcanic unit (not well exposed). Traverse northeastward for ~0.2 miles along the upper eastern flank of Fingerboard Mountain and stop and examine one of the larger exposures of sheared metadiorite.

Stop 4b: This outcrop is still within the Fingerboard Mountain Shear Zone, but we have crossed over the contact with the quartzofeldspathic gneiss and into a distinctively coarse-grained, sheared mafic metaplutonic rock, here referred to as the Lake Tiorati Metadiorite (after Gates et al., 2001c). This particular outcrop is part of a relatively large body that is ~200-300 m thick and is ~5-6 km in length located on the west side of Lake Tiorati (originally mapped by Dodd, 1965). The mineralogy of the rock at this locality is essentially all hornblende and plagioclase, with minor clinopyroxene and biotite. Foliation, defined by compositional layering, strikes northeast and dips steeply (~65°) to the northwest. Interestingly, mineral lineations plunge steeply to the northwest, indicating local thrust or normal motions on this part of the shear zone. The metadiorite is also cut by an undeformed granite pegmatite on the top of the outcrop.

Walk east-southeast, directly downhill toward Lake Tiorati for about ~0.2 miles. Reach the base of the hill and Seven Lakes Drive and then walk a few hundred meters northward to a small roadcut marked by a stick placed into a drill hole near the top of the outcrop.

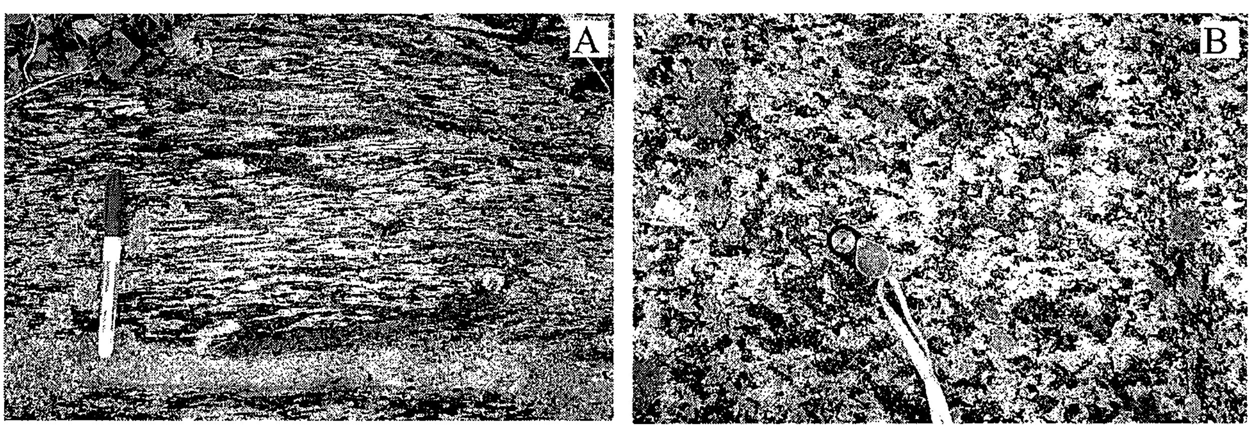


Figure 13. (A) Pavement surface of sheared Lake Tiorati Metadiorite from the summit of Blackrock Mountain ~5 km southeast of Stop 4c. Pen is oriented NW-SE. (B) Undeformed metadiorite from Stop 4c.

Stop 4c: This outcrop is the type locality for the Lake Tiorati Metadiorite and is located near the eastern margin of the Fingerboard Mountain Shear Zone. It is part of the same large body as mentioned in Stop 4b (Fig. 12A). At the southern end of the outcrop, the rock is essentially undeformed with good igneous textures developed (Fig. 13B). The diorite is composed mostly of plagioclase, hornblende, and clinopyroxene with minor orthopyroxene, magnetite and ilmenite. The orthopyroxene occurs as brown cores surrounded by coronas of clinopyroxene and/or hornblende. There is also a large xenolith of well-foliated biotite-plagioclase-quartz (metasedimentary) gneiss in the upper part of the outcrop. In the central and northern parts of the exposure, the diorite is cut by several anastomosing mylonite bands. The mylonite strikes northeast and is near vertical. Lineations plunge shallowly to the northeast. Kinematic indicators include rotated porphyroclasts and S-C fabrics (Fig. 13A). Where it can be determined, shear sense is consistently dextral. Recent SHRIMP U-Pb dating of small, subhedral zircons with minimal zoning obtained from undeformed metadiorite from this outcrop yielded a cluster of concordant ages averaging 1008 ±4 Ma (Fig. 6). Since this body is clearly cut by right-lateral ductile shear zones, this age provides an upper limit on the ductile deformation event that produced the Fingerboard Mountain Shear Zone.

Whole-rock major and trace element chemistry of samples from this outcrop indicate a mafic (~50% SiO_2, see Table 1) calc-alkaline, arc-like affinity for these rocks (Figs. 7A and C). We interpret the arc signature in these rocks to have been inherited from the continental lithosphere during magma generation and emplacement, and thus they do not indicate that there was active subduction zone in this part of the Grenville at the time. Therefore, based on field relations, geochronology, and geochemistry, the Lake Tiorati Metadiorite is best interpreted as a syntectonic, mafic plutonic rock that was emplaced just prior to or synchronously with a major right-lateral, ductile shearing event.

32.0 Proceed ½ of the way around Tiorati Circle, continue to follow Seven Lakes Drive and signs for Bear Mountain.

35.6 Again proceed ½ of the way around major traffic circle and follow NY Rte 6 East.

36.2 Large roadcuts of metapelitic gneisses on right (southeast) side of highway.

37.6 Very large roadcuts on the right (sourhern) side of highway of classic Storm King Granite gneiss on the northern flank of the Bear Mountain pluton. Nearly continuous outcrop for next 0.5 miles to the east.

38.6 Bear Mountain Circle. Proceed ¼ of the way around circle, following signs for NY Rte 9W South and US 202 West. Immediately turn right on Hessian Drive. Park in nearest lots for park lodges. Walk north ~0.1 mile, through middle of traffic circle, to prominent, but low, roadcut on the northern side of the circle and on the east side of NY Rte 9W.

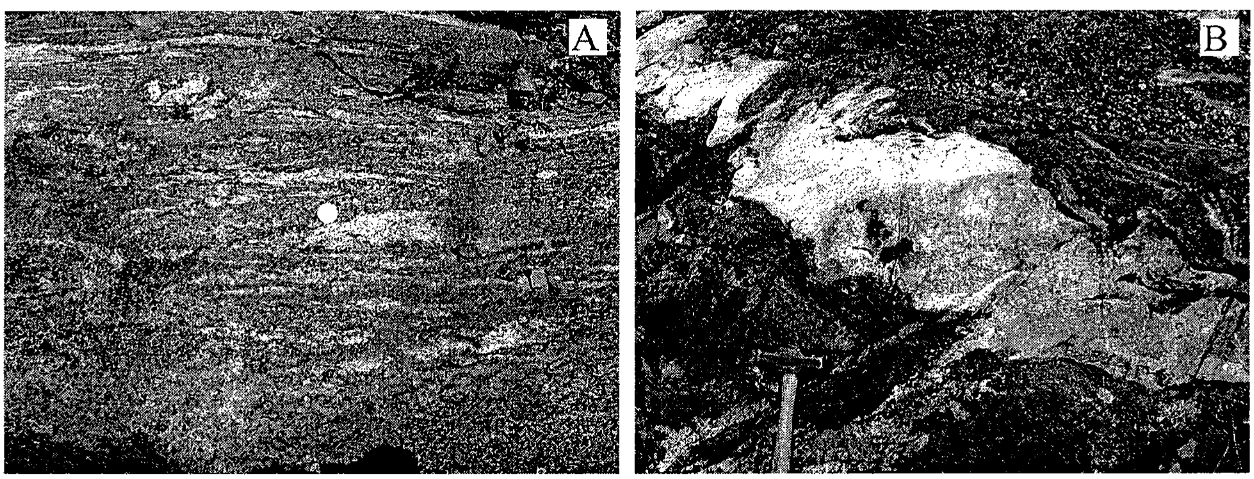


Figure 14. (A) Stromatic migmatite at Stop 5 (view is to the NE, down-plunge of the mineral lineation). Paleosome (gray rock) is Grt+Bt+Qtz+Pl+Sil schist with discrete and sub-concordant lenses and elongate pods of granitic rock in leucosomes (light gray) bound by thin concordant melanosomes composed of Bt+Grt+Sil (dark gray). The residual composition and texture of the paleosome suggests melt loss after partial melting of a pelitic protolith. (B) Sub-concordant granite sheet (Canada Hill granite?) in residual composition diatexite (Bt+ Grt+Sil schist). The composition and textures of the diatexite are consistent with extensive melt loss from these rocks after advanced partial melting of a pelitic protolith.

STOP 5: STROMATIC MIGMATITE, RESIDUAL DIATEXITE AND SHEETS OF CANADA HILL GRANITE.

In general, this exposure is typified by stromatic migmatite with local zones of residual diatexite in metaturbidite (Fig. 14A and B), presumably similar in protolith to that of rocks at Stop 1. The layered structure of this rock is moderately NE-dipping with a penetrative, yet variably oriented, moderately NE-plunging mineral lineation. Sub-concordant leucogranite sheets are penetrative, with one ~0.5 m-thick sub-concordant sheet at the structural bottom, and one at the structural top of the exposure. In views perpendicular to the main fabric (best at the top and south-facing parts of the exposure, the typical tripartite structure of the stromatic migmatite is seen where the rock is dominated by the Bt+Grt-rich host (melt-depleted) to cm-scale concordant lenses and sub-concordant elongate pods of Pl+Qtz leucosome bound and draped by mm-scale concordant Bt+Grt+Sil melanosomes. Locally, these rocks have distinctive cm-scale layers of Gr+Py+Grt with subordinate Bt+Qtz+Kfs+Pl+Sil lenses. The residual diatexite in this outcrop is defined by Grt+Bt+Pl+Sil (Grt is cm-scale) in apparently melt-depleted zones of the outcrop, typically associated with cm-scale granite sheets and pods. The diatexite shows ubiquitous apparent disruption of the host-rock structure, typically marked by an abundance of granitic material. Locally, the diatexite is apparently melt-enhanced (relatively more Pl+Qtz in the matrix) coincident with the most distrupted zones of the exposure, consistent with melt-enhanced granular flow of this rock during deformation. Each of these zones are delimited by a aggregate of cm-scale Grt and Bt melanosomes consistent with melt flow at the grain scale. Meter-scale dikes and sills of similar leucogranite to that found in this exposure are found in other exposures in the vicinity of West Point to the north may represent melt-escape structures to the melt lost from this rock.

39.1 Return to vehicles and turn **RIGHT** onto NY 9W South. (Unless you want to make an illegal move by cutting across dirt strip directly into the northbound side traffic circle!). **U-TURN** at "false entrance" to the Bear Mtn Park at the large brown sign just before traffic light. Proceed back on NY 9W North toward Bear Mtn Circle.

39.5 Bear Mountain Circle. Proceed ½ of the way around and follow NY 9W North.

39.6 Bridge over deep canyon of the Popolopen Creek ("The Hell Hole") and views of Anthony's Nose and the Hudson River.

41.3 Beginning of ~1 mile long series of roadcuts on both sides of the highway in migmatite with prominent lenses and pods of leucogranite sheets (Canada Hill Granite).

42.2 Exit right following signs for NY 218 (West Point, Highland Falls). At top of exit ramp, make a very hard LEFT on 218. Cross the bridge over NY 9W.

42.3 Park on the right side where a very wide shoulder exists at the entrance to James I. O'Neill High School. Walk down entrance ramp to large roadcuts on both sides. Mind the traffic at this stop.

STOP 6: STROMATIC MIGMATITE AND CONCORDANT SHEETS OF CANADA HILL GRANITE

Large roadcuts along exit/entrance ramps on the west side of the NY Rte 9W expose excellent examples of migmatitic metapelites and several, thin (5-10 m) interlayered sheets and pods of distinctively blue-gray to white, leucocratic Canada Hill Granite at the northeastern margin of the Crystal Lake Pluton (Figs. 15 and 16A) (Heleneck and Mose, 1976; 1984). This outcrop was part of a Hudson Highlands fieldtrip (Trip B-1, Stop #5) run during the 48th NYSGA in 1976 (Helenek and Mose, 1976). It is also from this locality that Aleinikoff and Grauch (1990) obtained a conventional, multigrain, TIMS U-Pb zircon crystallization age of 1010±6 Ma for the Canada Hill Granite and 1010±4 Ma for thin leucosome from the migmatitic metapelite.

The Canada Hill Granite at this locality is a coarse- to very coarse-grained equigranular rock that is composed of quartz, white K-feldspar, and white to gray plagioclase in roughly equal proportions (Fig. 16B). Locally, Pl dominates this rock. Biotite is ubiquitous as the mafic phase with accessory amounts of sphene, apatite, and zircon. Garnet is locally abundant, especially near contacts with the enclosing migmatites and is interpreted to represent undigested xenocrysts from those rocks after prolonged anatectic erosion of migmatite schollen. The host rock to the granite is stromatic migmatite with a strongly residual Bt+Grt+Pl+Qtz+Sil composition. Locally, the migmatite is schollen in the granite sheets with apparent anatectic erosion at the edges. The structure is regional (N30E, moderate SE-dip). Contacts between the migmatite and granite are typified by irregular structure and aggregates of Grt+Bt (cm-scale garnet), 1-3 cm thick. This is best seen in the exposure on the outside of the ramp (Figs 16A and B). Exposures in the median of the ramp show folded stromatic migmatite. The granite is predominantly massive textured with only local development of a weak foliation associated most commonly at contacts with migmatite host

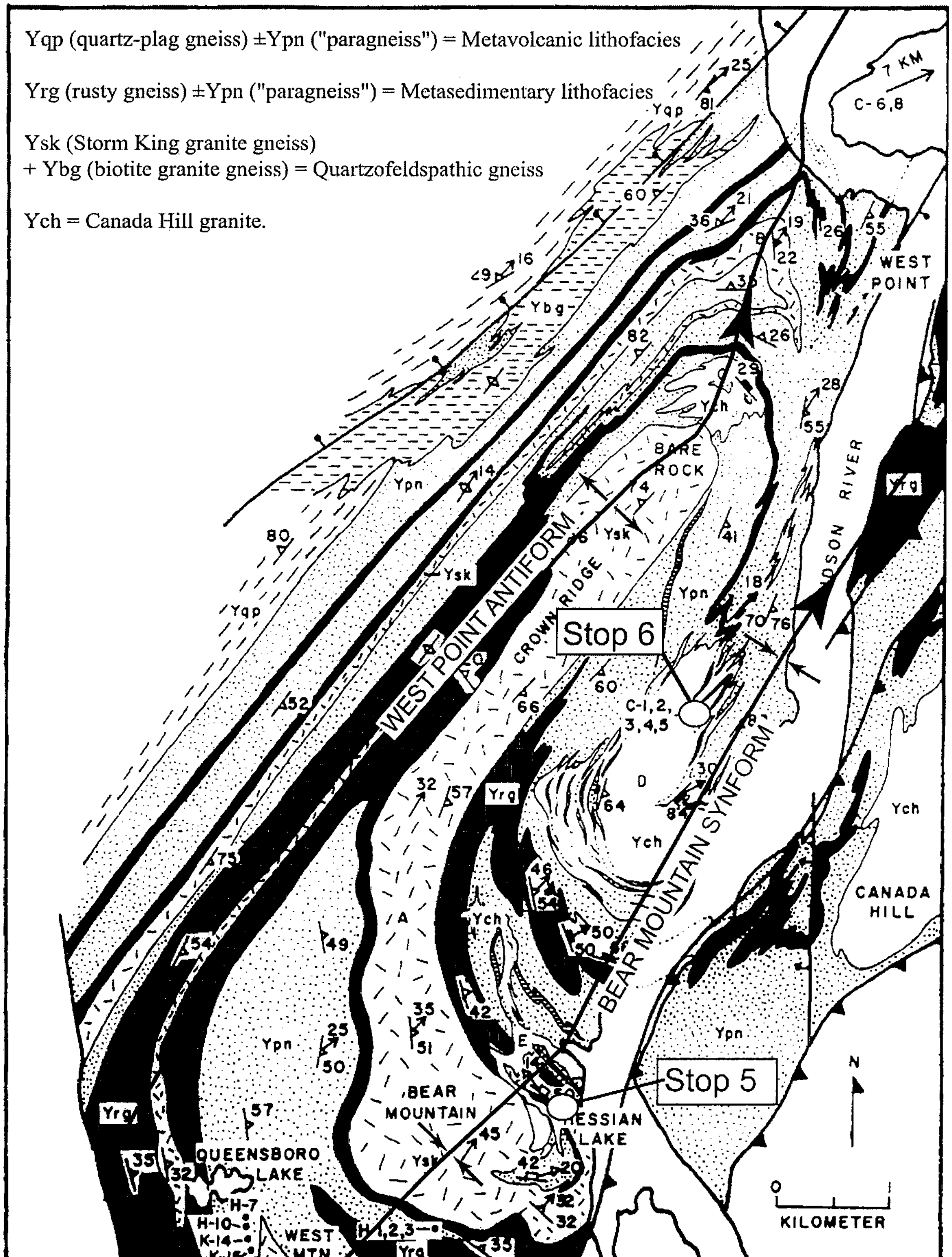


Figure 15. Geologic map of West Point - Bear Mountain area modified from Helenek and Mose (1984). Stop 6 is on the northeastern margin of the Crystal Lake pluton (labeled D) of the Canada Hill granite. Explanation and correlation of rocks units with the nomenclature presented here is given above.

rocks. The Canada Hill Granite here is in sheet and pod form, concordant with the foliation in the surrounding moderately SE-dipping migmatite (~N30E, 60SE). Contacts are generally gradational and diatexitic, except locally where the granite truncates foliation in the migmatite. This is best seen at south end of the northern median outcrop where granite sheets cut foliation near the hinge zone of complexly folded stromatic migmatite. Similar crosscutting relations have been documented elsewhere in the Hudson Highlands. For example, Helenek and Mose (1984) and Ratcliffe (1992) observed the Canada Hill Granite cutting gneissic fabric elements within the Storm King granite gneiss, metapelitic, and metavolcanic rocks in the Popolopen Lake and Oscawana Lake quadrangles to the south and east. In the Bear Mountain area, Helenek and Mose (1984) found xenoliths of Storm King granite gneiss enclosed in Canada Hill Granite along the southern margin of the Brooks Lake Pluton. Helenek and Mose (1984) also noted a weak axial planar foliation and the location of Canada Hill Granite in the hinges of large-scale, broad, open, upright, plunging folds (e.g., Bear Mountain synform, West Point antiform, Fig. 15) and interpreted this to indicate that the Canada Hill Granite was syntectonic to and slightly deformed during a late-stage Grenville orogenic event. This event is constrained to be syn- or post-1010 ±6 Ma, based on the current U-Pb zircon ages of the Canada Hill Granite (Aleinikoff and Grauch, 1990).

END OF TRIP - Return to vehicles and head back to Reeves Meadow Visitor Center

45.2 Proceed down entrance ramp onto NY 9W South. At Bear Mountain Circle follow signs for NY Rte 6 West.
47.6 Take Exit 18 and continue to follow NY Rte West.
47.9 Proceed ½ of the way around traffic circle and follow signs for Seven Lakes Drive.
51.6 Lake Tiorati Circle. Proceed ½ way around and continue to follow Seven Lakes Drive.
54.9 Kanawauke Circle. Proceed ½ way around and continue to follow Seven Lakes Drive.
60.5 Turn LEFT into parking lot at Reeves Meadow Visitor Center.

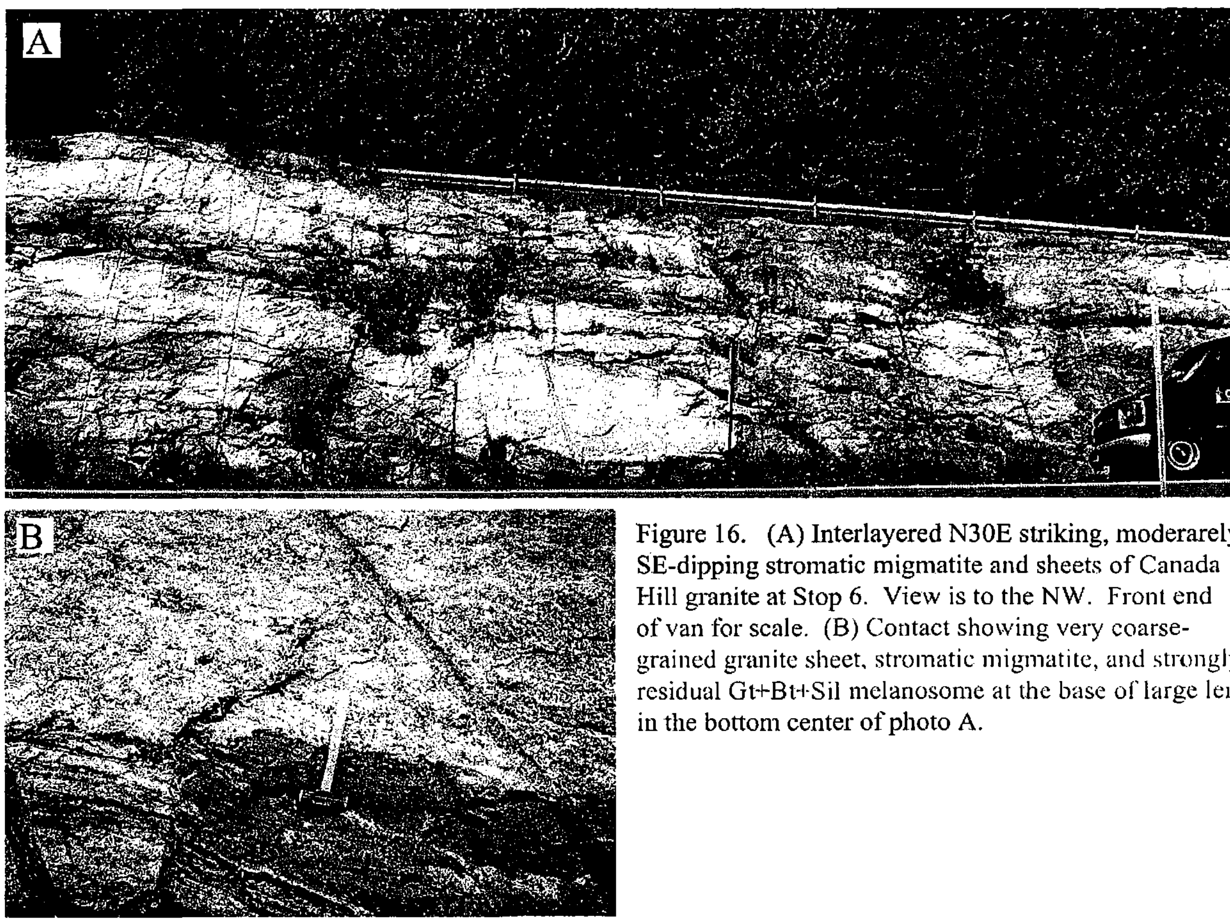


Figure 16. (A) Interlayered N30E striking, moderarely SE-dipping stromatic migmatite and sheets of Canada Hill granite at Stop 6. View is to the NW. Front end of van for scale. (B) Contact showing very coarse-grained granite sheet, stromatic migmatite, and strongly residual Gt+Bt+Sil melanosome at the base of large lens in the bottom center of photo A.